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MONITORING INTEGRATED ENERGY SYSTEMS AT A WASTEWATER TREATMENT PLANT IN MAINE

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16. ABSTRACT

A project was undertaken to monitor the performance of an integrated energy system at the Wilton, Maine, wastewater treatment plant. These systems included active and passive solar heating, effluent heat recovery, digester gas generation, air-to-air heat recovery, and electricity generation using digester gas. To accomplish the monitoring, an instrumentation system was installed and data were collected over the period from May 1979 to March 1981. This instrumentation system includes solar pyranometers, hydronic BTU computers, electrical and gas meters, a weather station, and numerous temperature transmitters. Data for the solar and digester systems are available in both digital and analog forms. The primary objectives of the project were:

1. To determine the effects of weather on systems performance.
2. To establish how much energy is used and/or produced by each system and its contribution to the various process and building requirements.
3. To determine the cost effectiveness for each system.
4. To review possible design and operational problems for improved performance.

A data analysis and engineering evaluation concluded that effluent heat recovery through the use of a heat pump and ventilation air heat recovery are cost effective; that the standard procedure for designing active solar systems based on instantaneous efficiencies can lead to significant overestimates of projected system performance, and that the use of solar thermal energy collection to supplement anaerobic digester heating is not cost effective.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a most vital communication link between the researcher and the user community.

The integrated energy systems monitoring of the municipal wastewater treatment plant in Wilton, Maine, analyzes the effectiveness of various energy conservation techniques and the uses of renewable energy such as active and passive solar heat, effluent heat recovery, exhaust air and cooling jacket heat recovery, and digester gas production.

Francis T. Mayo, Director
Municipal Environmenal Research
Laboratory

ABSTRACT

A project was undertaken to monitor the performance of an integrated energy system at the Wilton, Maine, wastewater treatment plant. These systems included active and passive solar heating, effluent heat recovery, digester gas generation, air-to-air heat recovery, and electricity generation using digester gas.

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This report was submitted in fulfillment of Contract No. 68-03-2587 by Wright-Pierce Engineers and Architects under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from August 11, 1977 to August 21, 1981, and work was completed as of May 28, 1982.

CONTENTS

Foreword iii
Abstract iv
Contents v
Figures viii
Tables ix
Abbreviations and Symbols x
Acknowledgments xi

1. Summary, Conclusions and Recommendations 1
    Summary 1
    Active Solar 5
    Passive Solar 8
    Heat Pump 8
    Generator Heat Recovery 9
    Digester Gas Generation 9
    Reflected Solar Radiation 9
    Electrical Usage 9
    Conclusions 10
    Recommendations 10
2. Facility Design 12
    Treatment Process 13
    Energy Systems 17
3. Energy Monitoring System 20
    Active Solar System 20
    Digester 21
    Effluent Heat Pump 21
    Passive Solar System 21
    Weather Data 21
    Electrical/Fuel Usage 21
    Exhaust Air Heat Recovery 22
    Domestic Hot Water System (DHW) 22
    Process Flow 22
4. Projected Energy Requirements and Production 24
    Projected Energy Requirements 24
        Building Heating 24
        Digester Heating 24
        Electrical Usage 25

Projected Energy Production 27
    Passive Solar 27
    Active Solar 30
    Emergency Generator 31
    Gas Boiler 31
    Heat Pump 31
    Summary 33

5. Actual Energy Requirement and Production 34
    Actual Energy Requirements 34
        Digester 34
        Domestic Hot Water 35
        Building Heating 36
        Heating and Ventilating Unit HV-1 36
        Heating and Ventilating Unit HV-2 36
    Actual Energy Production 36
        Passive Solar 39
        Active Solar 44
        Collector Efficiency 45
        Active Solar System Efficiency 51
        Emergency Generator 53
        Gas Boiler 53
        Heat Pump 53
        Domestic Hot Water (Electric) 56
        Digester Gas Generation 57
        Electrical Usage 63

6. Energy and Cost Effectiveness 64
    Passive Solar 66
    Active Solar 66
    Heat Pump 67
    Emergency Generator Heat Recovery 70
    Air-to-Air Heat Exchanger 71
    Digester Gas Generation 72

7. Operational Problems 74
    Collector Temperature Stratification 74
    Instrumentation Problems 74
    Digester Problems 75

8. Engineering Evaluation 76
    Hydronic Solar System 76
    Passive Solar Heating 78
    Heat Pump 78
    Instrumentation 78
    Digester Gas System Design 78

References 89

Bibliography 90

Appendices

A SI Conversions 92
B Building "U" Values 93
C OA and Ground Design Temperatures (Design & Actual)... 94
D Electrical Equipment Data and Operating Schedules 95
E Dowtherm SR-1 Specific Heat and Density Curves 96
F ASHRAE Mean Percentage of Possible Sunshine For Selected Locations 98
G Energy Usage Records 99
H Thermocouple Location (Active Collector) 100
I Specification Data for Heat Pump Emergency Electrical Generator, Gas Boiler and Air-to-Air Heat Exchanger. 101
J Data Verification 103
K Description of Anaerobic Sludge Digestion System and Digester Gas System 113
L Passive Collector Shading Factors 123
M Active Collector Specification Data 124
N EPA Cost-Effectiveness Analysis Guidelines and Detailed Present Worth Calculations 126

FIGURES

Number		Page
1	Total Energy Source Contributions	2
2	Energy Usage/Production Summary	3
3	Collection of Solar Radiation Throughout the Day	7
4	Wilton Treatment Plant	12
5	Wilton Treatment Plant Section	13
6	Floor Plans	15
7	Treatment Process Diagram	16
8	Energy Systems Conceptual Diagram	17
9	Heating System Flow Diagram	19
10	Monitoring Instrumentation Schematic	23
11	Passive Panel Transmissivity	41
12	Collector Performance Curve (Predicted)	49
13	Collector Performance Curve (Actual)	50
14	Heat Pump COP vs. Effluent Temperature	55
15	Heat Pump Cost COP Parameter	68

TABLES

Number		Page
1	Energy and Cost Effectiveness Summary	4
2	Monthly Summary and Solar Utilization	6
3	Projected Energy Requirements Summary	26
4	Net Passive Solar Contribution	27
5	Estimated Incident Solar Energy on Array	28
6	Estimated Net Energy Collection of Solar Array	29
7	Net Active Solar Contribution	30
8	Projected Energy Sources	32
9	Percent Energy Source Contribution	33
10	Digester Heating Summary	35
11	Air-to-Air Heat Exchanger Summary	37
12	Energy Contribution Summary - Users and Producers	38
13	Passive Collector Transmissivity	42
14	Passive Solar Energy Performance	43
15	Insolation	44
16	Shielded/Unshielded Insolation	47
17	Collector Performance Data	48
18	Active Solar System Efficiency Summary	52
19	Heat Pump Summary	55
20	Domestic Hot Water Heating Summary	56
21	Anerobic Sludge Digestion System Characteristics	58
22	Digester Gas Generation Summary	62
23	Total Electrical Usage	63
24	Construction Cost Estimate Summary	65
25	Energy and Cost-Effectiveness Summary	73

ABBREVIATIONS AND SYMBOLS

ASHRAE -- American Society of Heating, Refrigeration, and Airconditioning Engineers
CFM -- Cubic feet per minute
BTU -- British thermal unit
SCF -- Standard cubic foot
KWH -- kilowatt hour
BTUH -- British thermal units per hour
I -- Incident solar radiation
A -- Area
U -- Heat transfer coefficient
MBTU -- BTU x 10^6
OAT -- Outside air temperature
BHP -- Brake horsepower
HV -- Heating and ventilating
EF -- Exhaust fan
DHW -- Domestic hot water
GWT -- Ground water temperature
TSP -- Total static pressure ("w.c.)
"w.c. -- Inches of water column (Gauge)
PF -- Power factor
°C -- Temperature, degrees Celsius
J -- Joules
kJ -- Joules x 10^3
MJ -- Joules x 10^6
GJ -- Joules x 10^9
kg -- Kilograms
M -- Meters
Pa -- Pascals
PW -- Present worth
MPa -- Mega Pascals

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The solar portion of this study drew on concepts presented in a previous investigation sponsored by the U.S. Environmental Protection Agency:

> Malcolm, Jess W. and Cassel, David E. Use of Solar Energy to Heat Anaerobic Digesters. Environmental Systems, Inc., Annapolis, MD 21401. EPA-600/2-78-114. July 1978.

The present project was co-sponsored by the municipal and energy research programs of the U.S. Environmental Protection Agency, Cincinnati, OH and the U.S. Department of Energy, Washington, DC.

SECTION 1

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

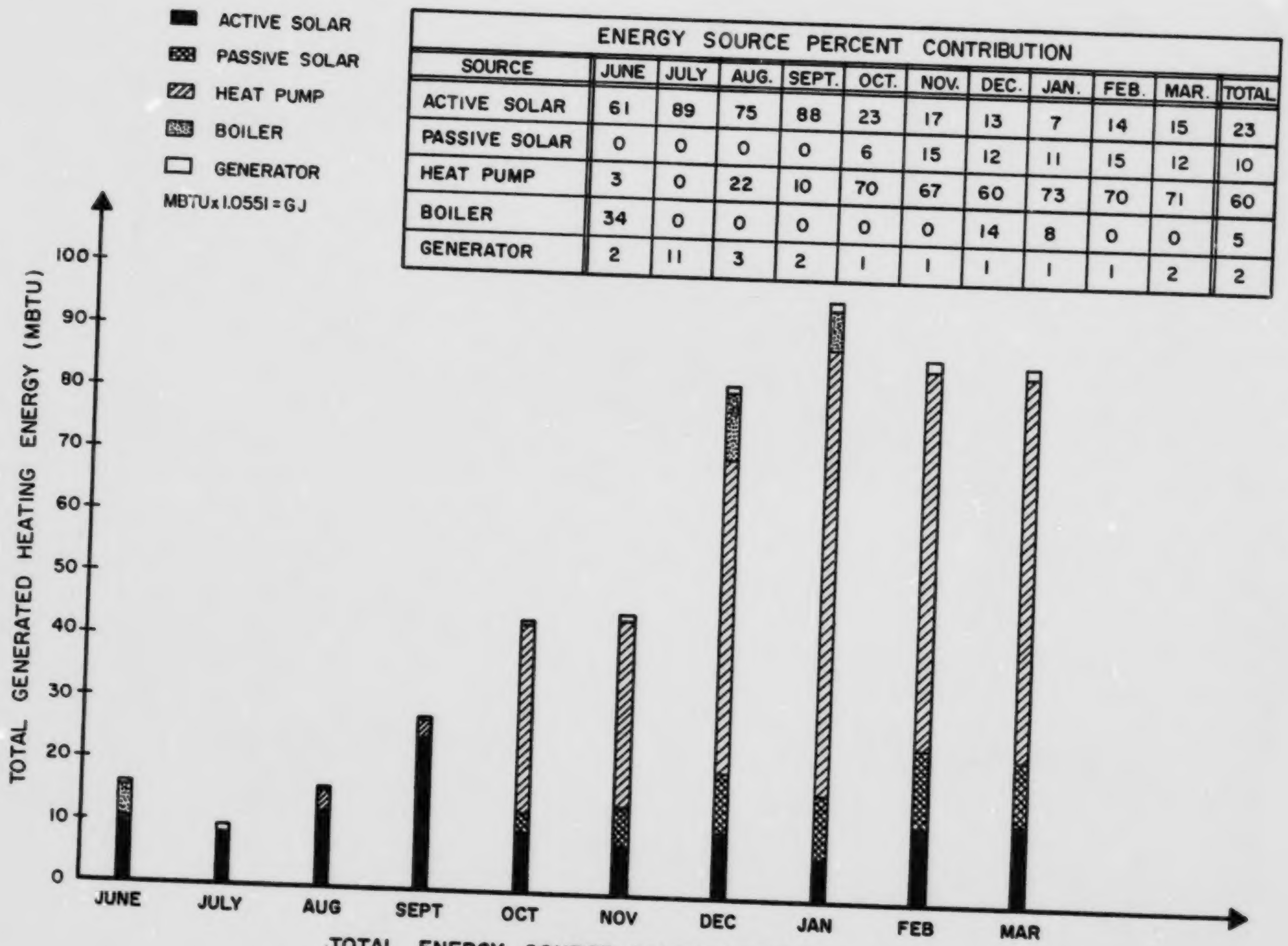
A. SUMMARY

A project was undertaken to monitor the performance of an integrated energy system at the Wilton, Maine, wastewater treatment plant. The system comprises two parts: (1) the heating system, consisting of active and passive solar systems, an effluent-to-water heat pump, a digester gas boiler, an air-to-air heat exchanger, and a heat recovery system on the emergency electrical generator; and (2) the digester system, consisting of primary and secondary digesters and high- and low-pressure gas utilization and storage systems. The objective of this project was to determine the actual operating parameters of each system and then to determine the ways in which they affected the other associated systems. The effects of varying weather conditions on these systems was also to be investigated, and projections of the cost-effectiveness of solar heating of anaerobic digesters were required.

The monitoring system was designed and installed based on anticipated performance. Generally, the equipment was of sufficient sensitivity and range to provide valid results. But various problems developed with some equipment during the monitoring period, and data were lost while repairs were made (see Section 7).

From available energy monitoring data, each major component of the heating system was analyzed and evaluated for its energy and cost effectiveness. The digester gas production rates have been evaluated using the limited data gathered.

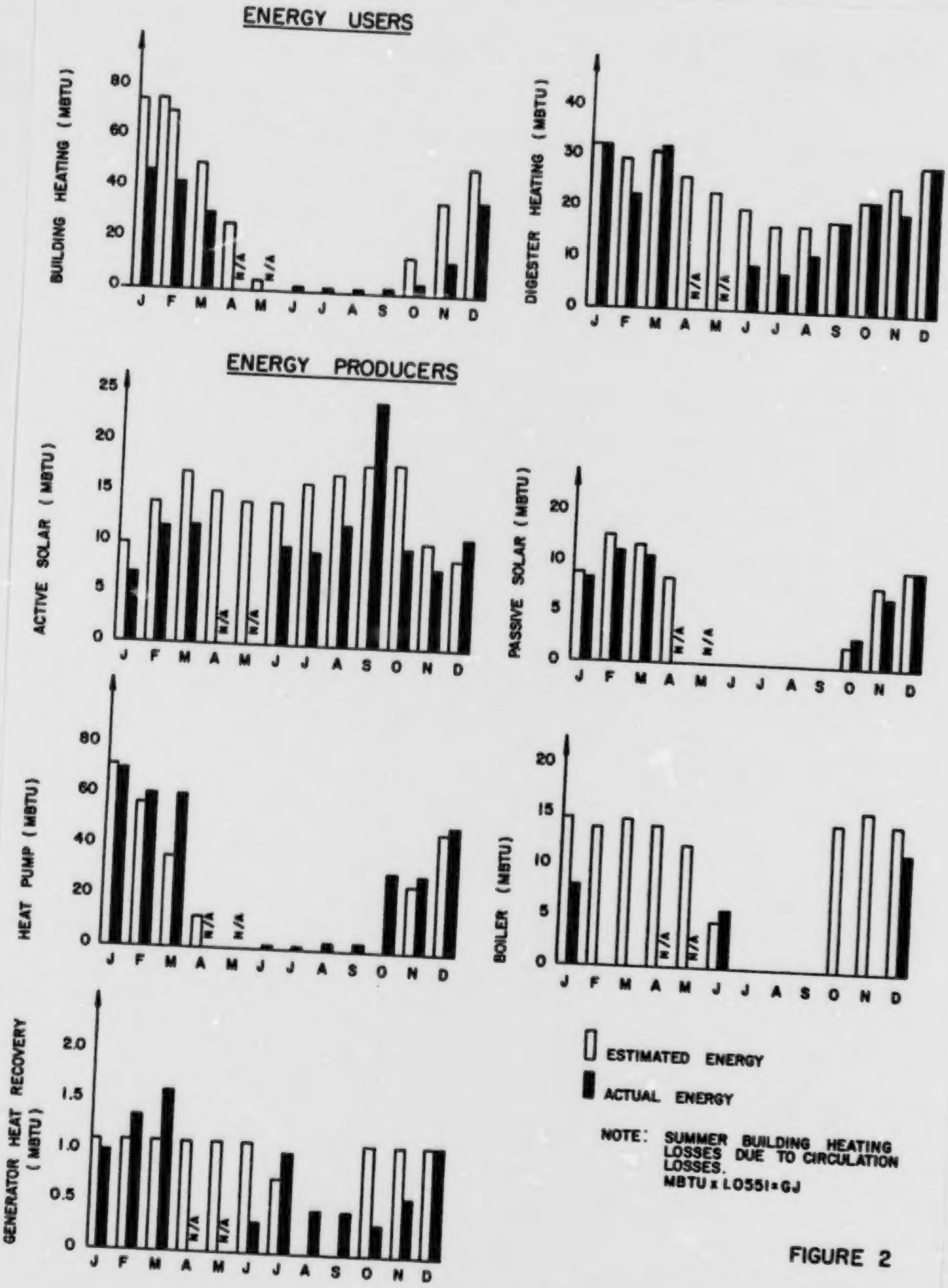
Figure 1 illustrates the total energy produced by the heating systems according to each component's contribution. This figure does not include the electrical contribution made by the electrical immersion heater for the domestic hot water (DWH) system. Figure 2 shows energy usage and production. (The total source contribution, including the electrical DHW heating, is tabulated in Table 12 on an energy basis.) Table 1 summarizes the energy and cost effectiveness for various systems (see Section 6).



ENERGY SOURCE PERCENT CONTRIBUTION

SOURCE	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	TOTAL
ACTIVE SOLAR	61	89	75	88	23	17	13	7	14	15	23
PASSIVE SOLAR	0	0	0	0	6	15	12	11	15	12	10
HEAT PUMP	3	0	22	10	70	67	60	73	70	71	60
BOILER	34	0	0	0	0	0	14	8	0	0	5
GENERATOR	2	11	3	2	1	1	1	1	1	2	2

TOTAL ENERGY SOURCE CONTRIBUTIONS
FIGURE 1



NOTE: SUMMER BUILDING HEATING LOSSES DUE TO CIRCULATION LOSSES.
MBTU x 1.0551 = GJ

FIGURE 2

ENERGY
USAGE / PRODUCTION
SUMMARY

TABLE 1

ENERGY AND COST-EFFECTIVENESS SUMMARY

Component	Energy Output/ Input Ratio (1)	Value Output/ Input Ratio (2)	Cost-Effective
Active Solar	11.5	3.5	No
Passive Solar	32% (3)	N/A	No
Heat Pump	2.9	1.5	Yes
Generator Heat Recovery	113	86	No (4)
Air-to-Air Heat Exchanger	9.0	6.1	Yes
Digester Gas Production	0.59	0.72	No

[1] The Energy ratio is the total energy produced divided by the energy input required.

[2] The Value Ratio is the dollar value of the energy produced divided by input energy cost.

[3] Actual average monthly solar radiation transmitted through panels from June 1, 1979 to April 1, 1980 (see Chapter 5).

[4] Due to low usage; if used more, it could be cost-effective.

From Table 1 it can be seen that each of the measures, except for the Digester gas production , was a net energy producer and net cost saver. However, the payback periods generally were greater than are economically justifiable.

Active Solar System

Table 2 summarizes the active solar system data between June, 1979 and April 1, 1980, collected as follows:

1. Recorded clear day insolation levels were consistently above ASHRAE estimates with an average difference of 13.8% (Item 9).
2. The recorded percent of possible sunshine was 60% versus an average of 52% predicted. This is consistent with the unusually low precipitation levels experienced.
3. The average incident solar radiation was 37.3% above that estimated (Item 11).
4. The total solar energy collected was 122 GJ (Item 16), which was 64% of that estimated.
5. The overall solar system efficiency, being the net energy collected divided by the total incident available, was 23% (Item 15).

An overall efficiency of 23% is significantly lower than that anticipated. A great deal of effort was spent in investigating the reasons which were presumed to be one or more of the following:

1. Data/Instrumentation error.
2. Collector Heat Loss Factor
   a. Inadequate thermal isolation.
   b. Possible convective losses between the absorber plate and the rigid insulation.
3. Collector Heat Transfer Losses
   a. Air within the fluid loop.
   b. Effect of the glycol solution.
4. Control sequencing and response.
5. Collector response sensitivity.
6. Collector efficiency losses due to dirt accumulated during construction.

Though all of these factors (excluding the first) certainly contribute to the solar system performance, the overriding cause appears to be the combination of all of them coupled with actual weather conditions and the lack of an accurate calculation procedure to simulate this interaction.

There is obviously a significant difference between instantaneous collector efficiency and day-long or, more importantly year-long collector efficiency. Instantaneous efficiencies are useful in comparing various types of collectors under similar steady state conditions, but tend to create a misleading picture of the efficiency of water heating systems operating over long periods.

Table 2

MONTHLY SUMMARY AND SOLAR UTILIZATION

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	See Note
1	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2	Days in Month	31	29	31	30	31	30	31	31	·30	31	30	31	
3	ASHRAE Clear Day Insolation (W/m^2) (A)	229	276	286	267	248	238	243	259	272	260	225	205	A
4	Grumman Clear Day Insolation (W/m^2) (B)	217	263	273	257	234	220	222	239	257	260	232	199	B
5	Mean Percent of Possible Sunshine (C)	43	51	53	53	57	62	63	61	58	54	39	38	C
6	Probable Available (4 x 5)	93	134	145	136	133	136	140	146	149	140	90	76	
7	Recorded Average Insolation (W/m^2 Day)	149	198	172	--	--	191	198	172	228	123	112	137	
8	Recorded Clear Day Insolation (W/m^2 Day) (D)	277	300	338	--	--	264	237	309	304	301	262	245	D
9	Recorded I/ASHRAE I (8 / 3) (E)	1.21	1.09	1.18	--	--	1.11	0.97	1.19	1.12	1.16	1.16	1.19	E
10	Recorded Clearness (7 / 8) (N)	0.54	0.66	0.51	--	--	0.72	0.84	0.56	0.75	0.41	0.43	0.56	N
11	Recorded I/Probable I (7 / 6) (F)	1.60	1.48	1.19	--	--	1.40	1.42	1.18	1.53	0.88	1.24	1.81	F
12	Probable Net Collected (W/m^2 Day) (G)	41	63	71	65	61	62	69	78	83	77	46	33	G
13	Actual Net Collected (W/m^2 Day) (H)	23	44	44	--	--	33	28	402	79	33	27	35	H
14	Net Collected/Probable Net (13 / 12)(I)	0.56	0.71	0.62	--	--	0.54	0.41	0.54	0.95	0.43	0.58	1.08	I
15	Net Collected/Recorded I (13 / 7 x 100)(J)	15.5	22.4	25.4	--	--	17.4	14.1	24.5	34.5	27.2	23.6	25.9	J
16	Total Solar Produced (GJ) (K)	7.45	13.25	14.06	--	--	10.31	8.93	12.90	13.16	10.67	8.22	11.33	K
17	Total Heating Load (GJ) (L)	101.63	92.16	91.54	--	--	16.96	9.99	17.16	29.33	46.58	47.24	87.44	L
18	Percent Solar (16 / 17 x 100) (M)	7	14	15	--	--	61	89	75	88	23	17	13	M
19	Average Daily Temperature (°C)	-7	-8	-1	5	11	17	22	17	12	8	4	-4	

A. Solar insolation for the 21st of each month, 44° latitude, 59° tilt from the horizontal, facing due south.

B. Solar insolation for the 15th of each month, 44° latitude, 60° tilt from the horizontal facing 2° west of south. Data used in original projections.

C. Tabulation derived from "Normals, Means, and Extremes" table in U.S. Weather Bureau publication, Local Climatological Data. 53 percent average using Albany, New York.

D. Actual clear day data recorded for each month.

E. 13.8 percent over ASHRAE clear day data.

F. 37.3 percent over probable available insolation.

G. Probable net collected 6x collector efficiency factors.

H. Net collected (water side of solar heat exchanger).

I. 64.2 percent of that estimated.

J. 23 percent of recorded incident solar collected.

K. For 119.5 m^2 collector surface, 122.9GJ/10 months.

L. Heating load includes process, transmission and ventilation loads.

M. 23 percent overall being supplied by solar.

N. Actual average percent of possible sunshine - 60 percent.

In the month of March, for example, approximately 1/3 of the incident radiation was of too low an intensity to collect. In many cases the collector plate temperature never reached a usable or threshold level although considerable insolation was available. An illustration of these losses in long term efficiency is shown in Figure 3 for a clear day. The corresponding losses for a cloudy day are obviously greater, particularly if the solar radiation intensity equals the critical, or threshold intensity.

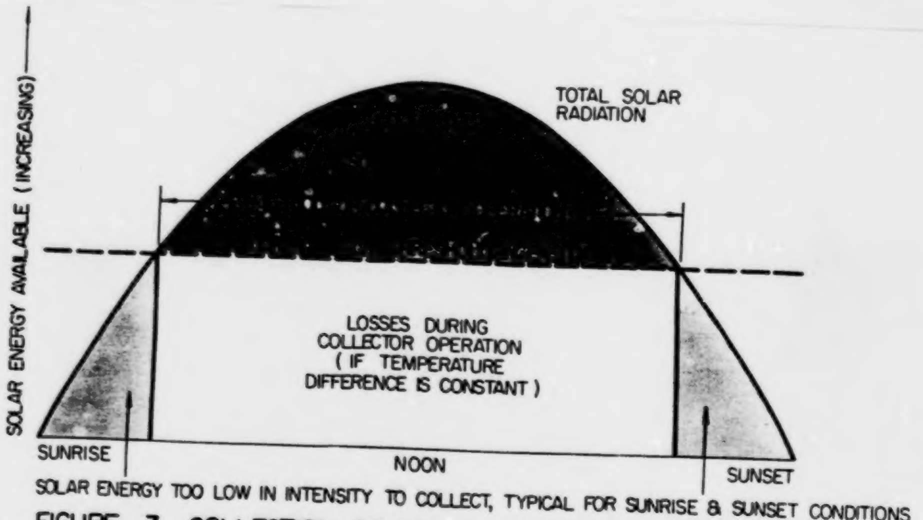

SOLAR ENERGY AVAILABLE (INCREASING)
TOTAL SOLAR RADIATION
LOSSES DURING COLLECTOR OPERATION (IF TEMPERATURE DIFFERENCE IS CONSTANT)
SUNRISE
NOON
SUNSET
SOLAR ENERGY TOO LOW IN INTENSITY TO COLLECT, TYPICAL FOR SUNRISE & SUNSET CONDITIONS

FIGURE 3 COLLECTION OF SOLAR RADIATION THROUGHOUT THE DAY

The dominant factor in establishing the threshold intensity level is the temperature difference between the absorber plate and the ambient air. If this difference is minimized by either a warmer climate or a cooler collector fluid, as in the case of a heat pump assisted system, or both; then this threshold level would be reduced and the long term system efficiency improved. For example, in the case of a heat pump/solar system with an average collector fluid temperature of 10°C and an ambient temperature of 24°C, the threshold intensity level would actually be negative, enabling the system to collect heat without solar radiation.

As indicated, the causes were investigated for the lower overall efficiency based on the assumption that the estimating procedures were accurate. Numerous alternative procedures were studied with similar inflated results. In the course of the investigation several publications were discovered which included test data for actual solar systems monitored for a one year period. The results of these studies are similar to the findings to date at the Wilton plant. Each of the systems monitored consisted of flat plate collectors, non-selective coating, with two glass covers. The first involved a 50 m^2 solar system located in

Morton Grove, Ill. This system was monitored in 1975 by the Fluid Handling Division of ITT and had an overall efficiency of 21%[1]. The second system was located in Fort Collins, Colorado. It was monitored for one year by the Solar Energy Applications Laboratory at Colorado State University and had an overall efficiency of 19%[2].

Passive Solar System

The passive solar array is built into the wall at two levels. Solar radiation passes through the array providing both heating and lighting in the Clarifier Room. Each bank of panels has an overhang which tends to shade them during the summer months when heating is not required. Operable windows cool the space when the temperatures become excessive. The energy collected during these times is lost and, therefore, not considered useful.

Increasing the transmissivity and/or decreasing the "U" factor would increase the net quantity of collected solar radiation. More would be provided as useful during the winter but more would have to be dumped during the summer. For the panels, varying the ratio of transmissivity/"U" factor and estimating the net energy collected would provide an indication of what a change in that ratio would do to the system. Other factors such as overhangs, the blocking effect of the internal panel spacers, and variations in transmissivity with incident angle also need be considered.

For this installation, the variation in overall performance appears adequate, transmissivity increasing during the winter, decreasing during the summer. The overhang is responsible for a decrease in transmissivity during the summer up to a daily average of 14 percent.

Heat Pump

The heat pump operating time was greater than anticipated during this period. The Coefficient of Performance (COP) was quite acceptable during the heating season. The generation of the heating energy gave a net cost savings and the payback period was reasonable(11 years). Had the heat pump operating time equaled the projected operating time, the payback period would have been closer to 25 years, which is still reasonable.

The actual and projected hours of operation are based on operating conditions during the monitoring period, for which digester gas production was very low. As the plant flow rates increase and digester gas production increases, the heat pump will be used less with an increasing payback period due to less operation time.

To date, the operation and maintenance problems encountered have been relatively small. A good deal of time, however, has been spent in cleaning the effluent strainers. Records should be kept for several years to determine realistic O&M costs for the system.

Generator Heat Recovery

The generator heat recovery loop operated approximately one half hour per week during the generator exercise period. During part of that time, the recovery loop was not used because the storage tank temperature was warmer than the maximum generator cooling heat exchanger allowed. Town water was then used to cool the generator. This condition will arise regularly during the summer when there is a limited heating demand and the active solar system is able to provide most of the heating required.

The generator could be operated for longer periods of time during the heating season when digester gas is available.

The generator heat recovery loop has the highest energy output/input ratio, but the payback period is the worst. This is due to the low periods of use being experienced.

Digester Gas Generation

The digester gas generation system is, from Table 1, an energy and value loser. However, process requirements must also be considered when evaluating this system.

Reflected Solar Radiation

An attempt to measure the magnitude of the ground reflected solar radiation component met with limited success. From Chapter 5, the reflected component for peak nonclear days was within the experimental accuracy of the equipment being used. The average daily reflected component consists of both reflected and some diffuse solar insolation. Thus no meaningful data on the magnitude of the reflected componenet were gathered. Part of the reason for this was the minimal snow cover experienced during the winter of 1979-80.

Electrical Usage

Even with the heat pump operating more and the generator operating less than anticipated, the total electrical usage has been less than the projections of Chapter 4. The reduction for the 10-month monitoring period is 12.5%.

CONCLUSIONS

The results of the monitoring data analysis and engineering evaluation of the energy systems at the Wilton, Maine, wastewater treatment plant have led to the following conclusions:

1. Heat recovery from wastewater treatment plant effluent through the use of a water-to-water heat pump is cost effective under relatively severe temperature conditions.
2. Ventilation air heat recovery is cost effective.
3. Generator cooling loop heat recovery may be cost effective if increased use of the generator is warranted.
4. Passive solar heating, although not cost effective as analyzed for the Wilton plant, can be made cost effective with design modifications.
5. Solar system instantaneous efficiencies, when applied to clear-day insolation levels and the mean expected percent sunshine, may lead to an overly optimistic evaluation of the actual long-term performance. These losses are related to the system threshold insolution intensity and the random weather patterns. Thus it appears that computer simulation using averaged hourly weather data and system performance criteria is required to estimate the long-term efficiencies accurately. Moreover, since the threshold intensity level is predominantly affected by the difference in the average collector fluid and ambient temperatures, the long-term efficiency may be significantly reduced in northern climates.
6. Solar thermal energy collection for the purpose of producing supplemental heat for anaerobic sludge digesters is not cost effective under currently accepted economic projections, regardless of facility size.

RECOMMENDATIONS

The following recommendations are based on the work done on the Wilton Treatment Plant monitoring project:

1. A more realistic procedure must be developed for accurately estimating active solar heating system performance for the purpose of designing solar installations for space or process heating. Computer simulation models (taking into account site-specific hourly weather data, collection of system response time, and inherent system losses) should be developed to evaluate accurately the alternative solar designs for cost effectiveness during the preliminary design of a project.

2. Though the authors concluded that solar heating of anaerobic digesters is not cost effective, guidelines have been developed for significantly increasing the efficiency of this process if reasons other than conventional economics make such a system desirable. These guidelines can be found in Section 8, Engineering Evaluation.

3. Passive solar heating of treatment plant structures can be cost effective if applied to "occupied" areas such as the office and laboratory and if good energy conservation principles are followed in the design of such areas. This system is less cost effective when applied to process areas exposed to water surfacrs. In the latter case, it is important that room thermostats be set at 5 °C, a temperature that can largely be maintained by the water passing through these areas. Combined with task heating (if necessary) and proper energy conservation design, passive solar heating and lighting can be cost effective in process areas.

4. Effluent heat recovery through the use of a heat pump is cost effective. Operational problems can be minimized by properly designing the effluent sump from which the heat pump draws to provide sufficient capacity at minimum plant effluent flows.

5. Instrumentation and controls should be simplified as much as possible. The theoretical advantages of integrated energy systems can be offset by complicated trouble-prone instrumentation.

6. The available evidence indicates that solar heating of anaerobic digesters is not cost effective in accordance with the EPA guidelines, regardless of treatment facility size. Thus, we recommend that EPA not promote this concept and that they require exhaustive supporting documentation for any grantee requesting EPA Construction Grant Program funds for the design and construction of such facilities.

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SECTION 2

FACILITY DESIGN

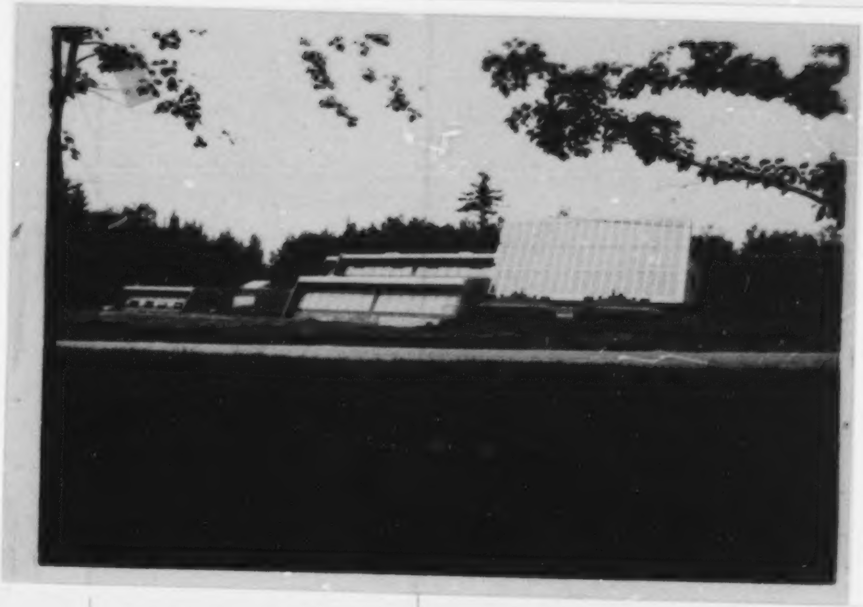

Figure 4. Wilton Treatment Plant

The overall objective of the architectural and engineering design of the treatment plant was to integrate the sciences, creating a totally unified economical project employing complementary systems and building configurations. The latest technological advances were brought into play where applicable. Special emphasis was placed on reducing the need for energy. This has been accomplished through the use of alternate energy sources, low energy requiring process equipment, and a combination of good engineering and architectural design principles. Due to Wilton's cold climate, the entire plant was enclosed in two structures (see Figures 4 and 6). To save on energy, unit processes were brought close together, while still providing for future expansion. Gravity was used wherever feasible to avoid the use of pumps. The control building was well insulated and zoned to enable different rooms to be heated to different temperatures. It was constructed of concrete block and brick with insulation between to provide a large mass to hold the heat at night. The roof was designed to hold snow to provide good natural insulation. The building was built into a hillside, with little exposure to the north, to

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minimize the exterior surface. This results in lower demands for heating, lighting and system loads.

The most significant innovation which was meant to reduce the requirements for "off site energy" is the application of solar energy, which for the first time was used in a sophisticated manner as an integral part of the wastewater treatment process. The enclosing structures were oriented southward to achieve maximum value from the sun's direct energy through both passive and hydronic solar energy collection devices. Passive solar collection was achieved through the use of fiberglass panels which let solar heat into the process rooms of the plant to directly heat the air, without letting the heat out (Figure 5). Black metal solar collector panels, set at a 60° slope, formed the south roof of the treatment plant. An anti-freeze solution is pumped through these panels and heated to 49° to 60°C by the sun. Although this solar energy is used to heat the building and the hot water supply, its primary purpose is to provide heat for the anaerobic digesters.

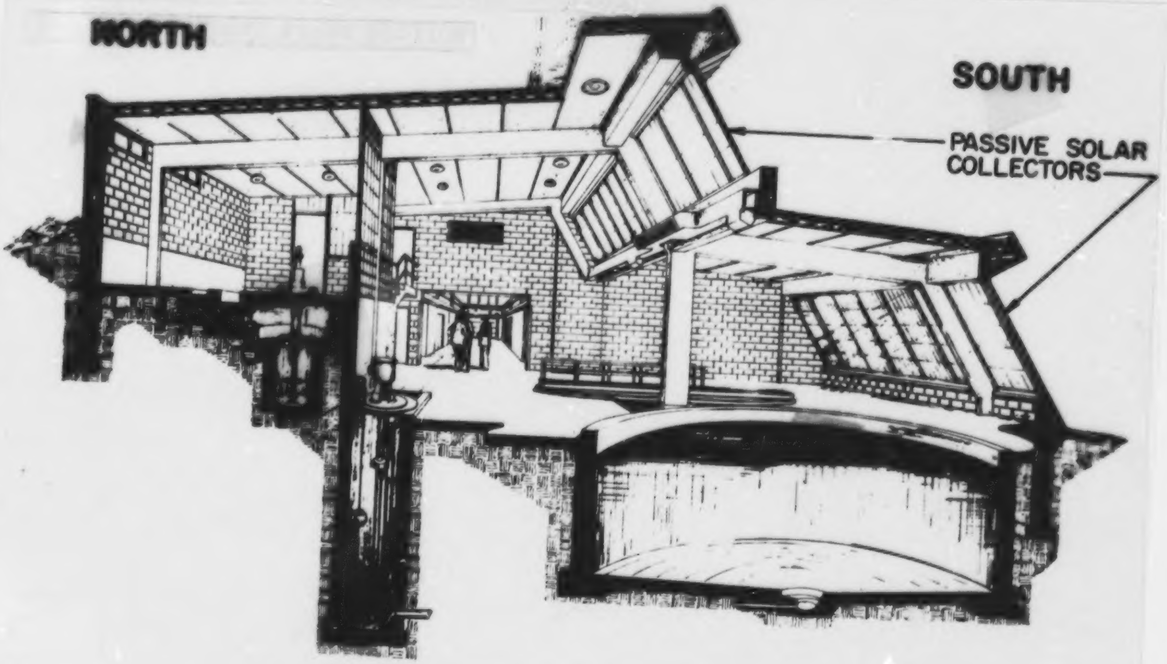


Figure 5. Wilton Treatment Plant Section

TREATMENT PROCESSES

The treatment processes, designed for simplicity of operation and maintenance, impact the energy systems via digester gas production and effluent heat recovery. Figure 7 is the plant's process flow diagram. Wastewater is lifted into the plant by screw pumps, which use less energy than conventional pumps, and automatically provide constant flow, thus preventing overloading of the treatment processes. The wastewater flow is by gravity throughout the rest of the plant, again conserving energy. Pre-treatment is provided by comminution and grit removal. Gross solids are removed by rotary screens. Secondary biological treatment is accomplished via the rotating biological contactor (RBC) process, which consists of shafts of plastic discs rotating in the wastewater, with biological masses growing on the discs and treating the sewage. This again is a low energy, low maintenance process. Final solids separation is accomplished in clarifiers, from which the solids are combined with the primary screenings and pumped to anaerobic digesters for stabilization before being dewatered and disposed; and the effluent is disinfected and normally discharged to the stream. The disinfectant is sodium hypochlorite, which is generated on-site electrochemically from salt and water, at a cost competitive to that of purchased chlorine gas, without the safety problems and uncertainty of supply.

Before disposal, sludge is stabilized in the anaerobic digesters which must maintain steady temperatures of approximately 35°C. Methane gas is evolved as a by-product of this digestion process and traditionally is burned to provide heat for the digester. In small treatment plants, such as this one, all the methane would normally be used to heat the digester. None would be available for other purposes, thus a large amount of auxiliary off-site fuel would be required, especially in the winter. The use of solar energy to heat the digesters, therefore, was meant to free the digester gas for use in heating the building, running the electric generator, and long term storage. This overcomes one of the main problems of solar energy, that of storage. Digester gas is a much more economical material to store than heated water, and it is also much more flexible in its use.

The treatment process and energy systems were coupled to produce more alternate sources of energy. Maximum excess heat energy, including excess heat from exhausted air, generator coolant, and effluent water is recovered within the building for reuse. The recovery of 60% of the heat from exhaust air in the ventilation system is used to preheat cold air drawn into the plant. The effluent from the plant normally is discharged at 7° to 10°C, even in the winter, which represents a potentially useable source of heat. By using an electric heat pump, the Wilton plant recovers much of this wasted heat, producing approximately three units of heat energy for every equivalent unit of electrical energy used. Not only does this help heat the building, but the resultant lowering of the effluent temperature prevents thermal shock on the stream, which may happen when relatively warm effluent is discharged to the cold waters of the stream in winter.

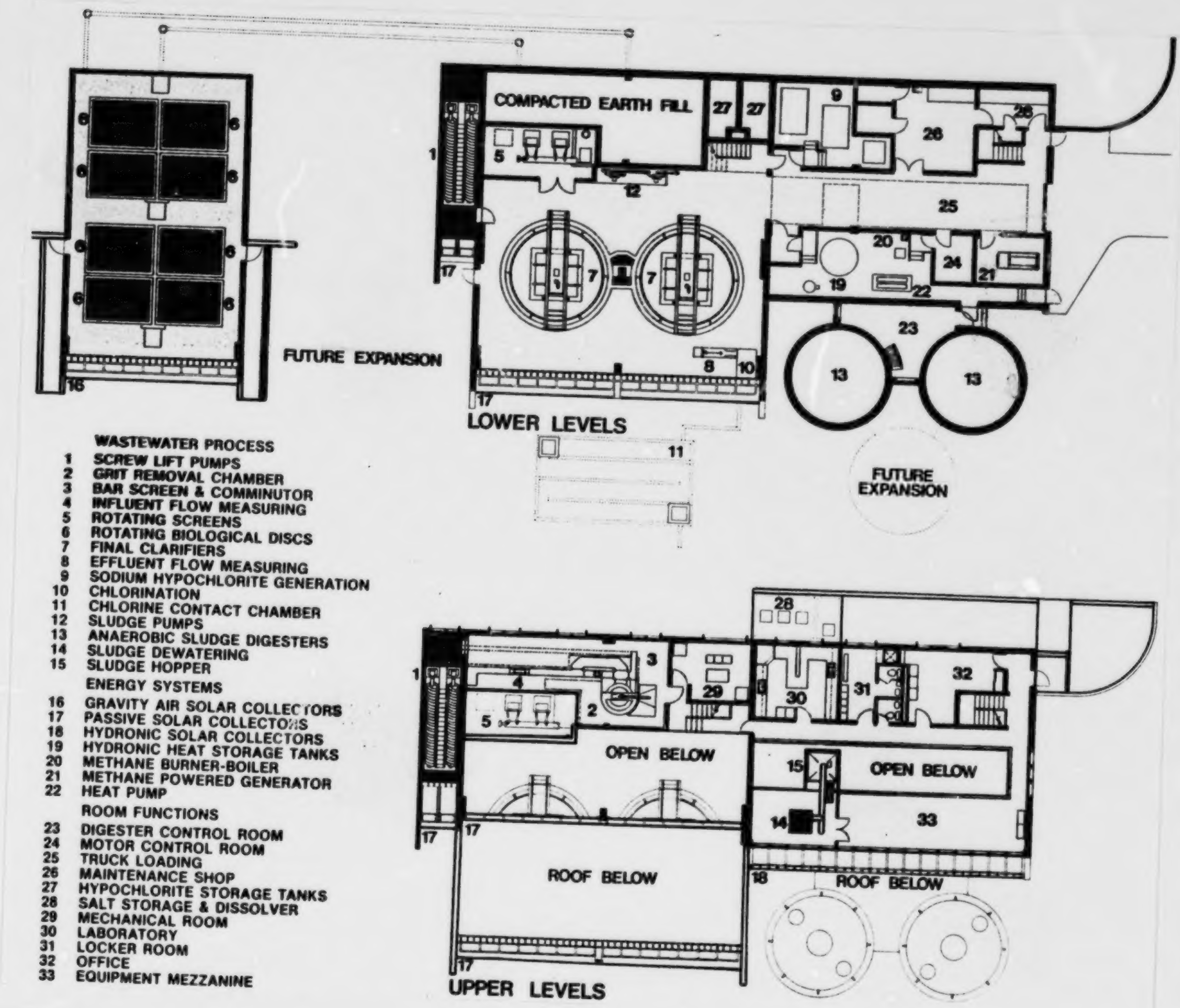
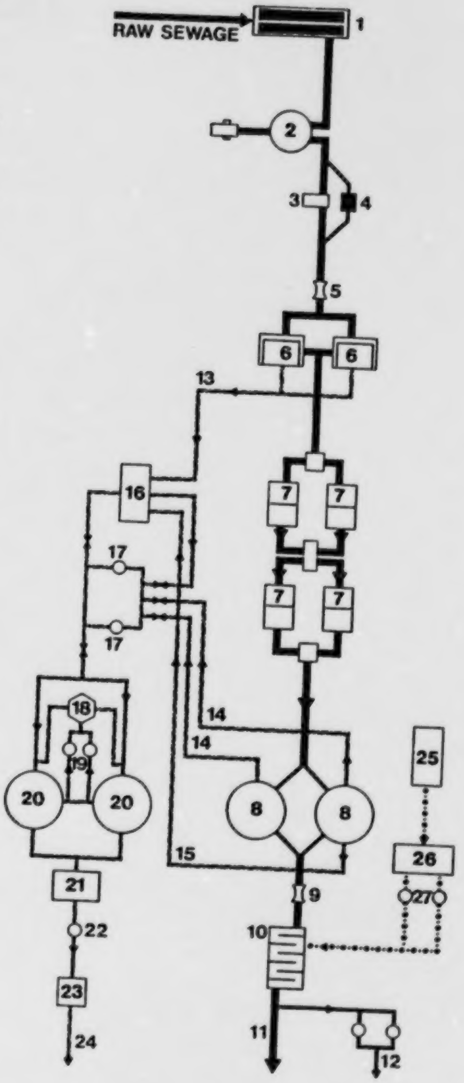

COMPACTED EARTH FILL
FUTURE EXPANSION
LOWER LEVELS
FUTURE EXPANSION
OPEN BELOW
OPEN BELOW
ROOF BELOW
ROOF BELOW
UPPER LEVELS
WASTEWATER PROCESS
1 SCREW LIFT PUMPS
2 GRIT REMOVAL CHAMBER
3 BAR SCREEN & COMMINUTOR
4 INFLUENT FLOW MEASURING
5 ROTATING SCREENS
6 ROTATING BIOLOGICAL DISCS
7 FINAL CLARIFIERS
8 EFFLUENT FLOW MEASURING
9 SODIUM HYPOCHLORITE GENERATION
10 CHLORINATION
11 CHLORINE CONTACT CHAMBER
12 SLUDGE PUMPS
13 ANAEROBIC SLUDGE DIGESTERS
14 SLUDGE DEWATERING
15 SLUDGE HOPPER
ENERGY SYSTEMS
16 GRAVITY AIR SOLAR COLLECTORS
17 PASSIVE SOLAR COLLECTORS
18 HYDRONIC SOLAR COLLECTORS
19 HYDRONIC HEAT STORAGE TANKS
20 METHANE BURNER-BOILER
21 METHANE POWERED GENERATOR
22 HEAT PUMP
ROOM FUNCTIONS
23 DIGESTER CONTROL ROOM
24 MOTOR CONTROL ROOM
25 TRUCK LOADING
26 MAINTENANCE SHOP
27 HYPOCHLORITE STORAGE TANKS
28 SALT STORAGE & DISSOLVER
29 MECHANICAL ROOM
30 LABORATORY
31 LOCKER ROOM
32 OFFICE
33 EQUIPMENT MEZZANINE

Figure 6. Floor Plan of Wilton Plant



1 SCREW PUMPS
2 GRIT CHAMBER
3 COMMINUTOR
4 BAR SCREEN BY-PASS
5 FLOW MEASURING & SAMPLING
6 PRIMARY SCREENS
7 ROTATING BIO-CONTACTORS
8 SECONDARY CLARIFIERS
9 FLOW MEASURING & SAMPLING
10 CHLORINE CONTACT CHAMBER
11 PLANT EFFLUENT
12 SPRAY IRRIGATION
13 PRIMARY SLUDGE
14 SECONDARY SLUDGE
15 SECONDARY SKIMMINGS
16 SLUDGE HOLDING
17 SLUDGE TRANSFER
18 SLUDGE HEATER
19 SLUDGE RECYCLE PUMPS
20 ANAEROBIC SLUDGE DIGESTERS
21 SLUDGE HOLDING
22 SLUDGE DEWATERING PUMP
23 DEWATERING UNIT
24 DEWATERED SLUDGE
25 HYPOCHLORITE GENERATION
26 HYPOCHLORITE STORAGE
27 METERING PUMPS

DESIGN CRITERIA

Quantity of sewage
$0.02\ m^3/s$

Influent BOD
200 mg/l (340 kg/d)

Influent suspended solids
200 mg/l (340 kg/d)

Effluent BOD
20 mg/l (34 kg/d): 90% removal

Effluent suspended solids
20 mg/l (34 kg/d): 90% removal

Sludge quantity to digesters
$9.5\ m^3/d$ at 3.5% solids

Methane yield
110 to $125\ m^3/d$

Methane heat value
$22{,}400\ kJ/m^3$ or 2.4 to 2.7 GJ/d

Figure 7. Flow Diagram for Treatment Process

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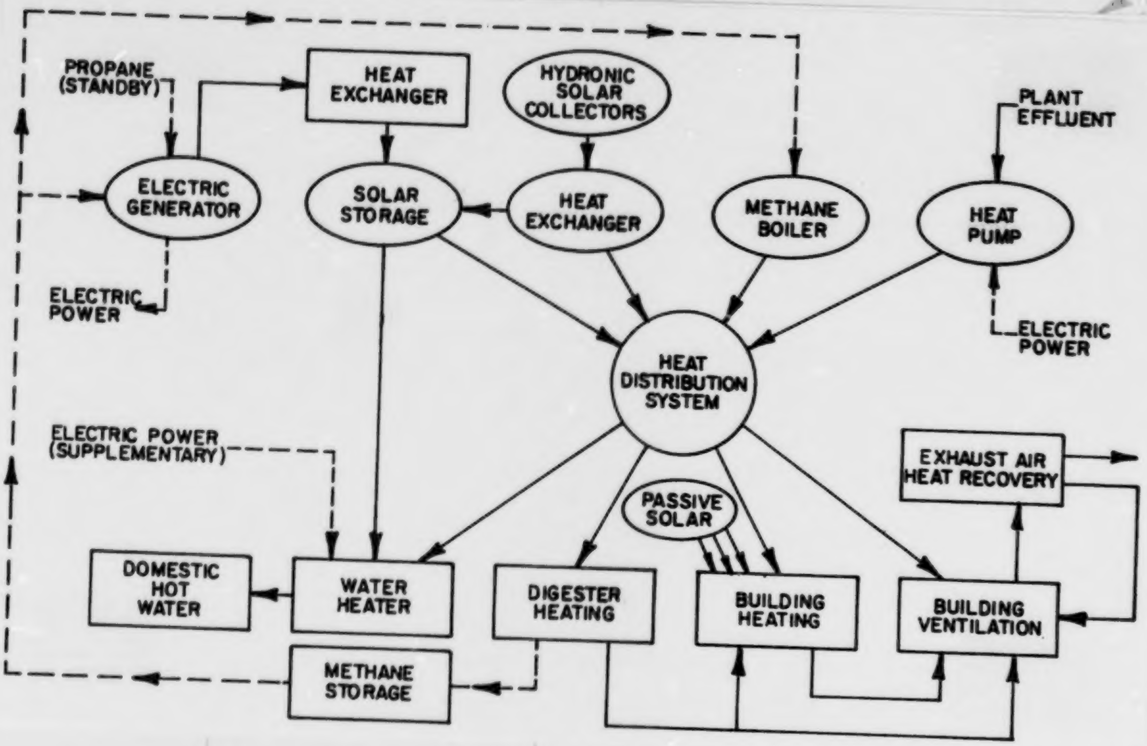
PROPANE (STANDBY)
HEAT EXCHANGER
HYDRONIC SOLAR COLLECTORS
PLANT EFFLUENT
ELECTRIC GENERATOR
SOLAR STORAGE
HEAT EXCHANGER
METHANE BOILER
HEAT PUMP
ELECTRIC POWER
ELECTRIC POWER
HEAT DISTRIBUTION SYSTEM
ELECTRIC POWER (SUPPLEMENTARY)
EXHAUST AIR HEAT RECOVERY
PASSIVE SOLAR
DOMESTIC HOT WATER
WATER HEATER
DIGESTER HEATING
BUILDING HEATING
BUILDING VENTILATION
METHANE STORAGE

Figure 8. Energy Systems Conceptual Diagram

ENERGY SYSTEMS

The conceptual energy flow diagram (Figure 8) indicates the interaction of the various energy sources and the heating requirements of the treatment plant. It is this interdependency of energy sources and the sophisticated control of them which make the energy system unique. The design is an integrated energy source and utilization system. The sources of energy can work individually, or in combination, in conjunction with the three basic heat utilization systems. The general philosophy is that the plant will use solar energy as the primary source, gas produced in the digesters as the secondary source, and the heat recovered from the process effluent by the heat pump as the back-up and final supplementary energy source. The generator will heat the plant as a primary source only in the event of a power failure, but it will provide power for general building use when excess methane is available.

The solar energy subsystem is a hydronic type with flat plate collectors 139 m^2 in area, an ethylene glycol/water collection loop, a heat exchanger, and storage systems. The solar collectors should collect

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between 230 and 270 GJ per year, while the passive collectors should add another 100 to 140 GJ per year. Ethylene glycol is circulated through collector plates which are heated from the sun's rays, and this energy is then exchanged to the plant's circulating water system.

The digester/methane subsystem is not especially unique in its function and design; however, the integration with the total system and its role in the energy conserving nature of the facility is unusual. The gas released becomes an important part of the total operation since it is used for the boiler in normal operation, and for the emergency electrical generator when excess gas is available.

The heating system flow diagram shown in Figure 9 indicates the complexity of the integration of the energy systems.

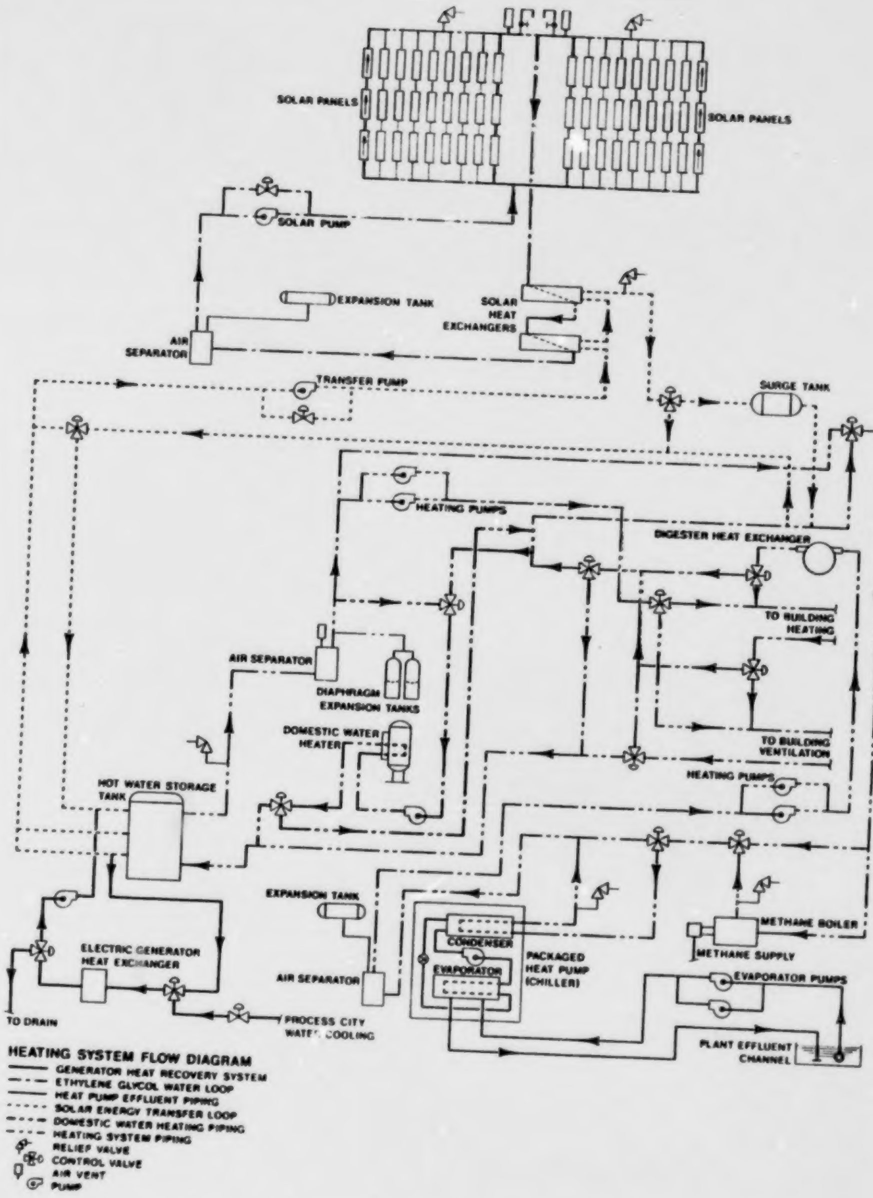
SOLAR PANELS
SOLAR PANELS
SOLAR PUMP
EXPANSION TANK
SOLAR HEAT EXCHANGERS
AIR SEPARATOR
TRANSFER PUMP
SURGE TANK
HEATING PUMPS
DIGESTER HEAT EXCHANGER
TO BUILDING HEATING
AIR SEPARATOR
DIAPHRAGM EXPANSION TANKS
DOMESTIC WATER HEATER
TO BUILDING VENTILATION
HEATING PUMPS
HOT WATER STORAGE TANK
EXPANSION TANK
METHANE BOILER
CONDENSER
PACKAGED HEAT PUMP (CHILLER)
EVAPORATOR
METHANE SUPPLY
ELECTRIC GENERATOR HEAT EXCHANGER
AIR SEPARATOR
EVAPORATOR PUMPS
TO DRAIN
PROCESS CITY WATER COOLING
PLANT EFFLUENT CHANNEL
HEATING SYSTEM FLOW DIAGRAM
GENERATOR HEAT RECOVERY SYSTEM
ETHYLENE GLYCOL WATER LOOP
HEAT PUMP EFFLUENT PIPING
SOLAR ENERGY TRANSFER LOOP
DOMESTIC WATER HEATING PIPING
HEATING SYSTEM PIPING
RELIEF VALVE
CONTROL VALVE
AIR VENT
PUMP

Figure 9. Flow Diagram of Heating System

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SECTION 3

ENERGY MONITORING SYSTEM

The objectives of the energy systems monitoring program are to predict, verify, and summarize the performance of the building thermal systems, especially in the digester area, on a totally integrated basis that is not available through predictive analysis of individual components.

These objectives are tied very closely to the basic energy conserving design of the plant itself, which is represented in Figure 10. Each subsystem is not especially unique in design by itself, however, the integrated subsystems pose complex problems in the interaction of process variables. This is especially prevalent in interaction between energy sources, i.e. solar input, methane boiler, heat pump and energy users, i.e. digesters, building heating and ventilation.

The integration of these subsystems is unique, and the design has been based on data provided by solar, emergency generator, boiler and digester manufacturers who have detailed knowledge of their system but limited knowledge of the total system. It is in these areas that the system is monitored to determine how the components interface.

ACTIVE SOLAR SYSTEM

In this subsystem an ethylene glycol water solution is circulated through collector plates which are heated from the sun's rays. This energy is then exchanged to the plant circulating water system. An underlying design premise is to use solar energy whenever it is available, with the use a function of exchanged temperature. The total performance of this subsystem needed to be determined.

Solar insolation was measured (for (1) direct, diffuse and reflected and (2) direct and diffuse only) and continuously recorded on a strip chart with an integrated digital output as well. Solar plate temperature and glycol flows and temperatures were also recorded. A hydronic BTU computer monitored the total heat from the solar heat exchanger for both analog and digital recording. Electrical input to solar pumps was also monitored.

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One of the major loads which the solar system supplies is the digester heating, as described in the following section.

DIGESTER

This subsystem again is not especially unique in its function and design, however, the integration with the total system and its part in the energy conserving nature of the plant is unique. The digester gas released becomes an important part of the total operation, as it is used in the gas boiler in normal operation and the emergency generator when excess gas is available.

A determination was made as to the quality and quantity of gas produced and where it is used. The properties and quantities of the sludge flow in and out of the digester, sludge and digester temperatures and the heating and electrical requirements were monitored.

EFFLUENT HEAT PUMP

The heat pump is a unique subsystem extracting heat from the effluent and converting it for use in the heated water system.

Electrical input and heating output were monitored continuously with digital outputs. Additionally, temperature and pressure drops across the evaporator and condenser and the auxiliary pump electrical usage were monitored. The unit coefficient of performance was determined for various conditions.

PASSIVE SOLAR SYSTEMS

Light/heat transmitting panels are employed in this plant. Their contribution to the total plant energy provides useful design data for scaled-up plants.

Solar insolation and solar transmissivity were measured and continuously recorded. Space temperature and heating requirements were also monitored to give an indication of the massive construction heat storage effect.

WEATHER DATA

All calculations for this plant are based on weather data provided by the National Weather Bureau. Environmental conditions were monitored for Wilton, Maine which can then be used as a correlation for actual plant performance especially in solar input as a function of ambient temperature, wind velocity, etc. at seasonal times of year.

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ELECTRICAL/FUEL CONSUMPTION

This plant was designed electrically and equipment sized for high efficiency, high power factor and low energy consumption. High pressure sodium lighting was employed where possible with selective switching and task lighting. Equipment was arranged for selective running from emergency generator depending on gas production.

All significant electrical usage was monitored and audited by function so the total energy requirements for systems such as solar could be determined.

Digester gas production and propane usage were recorded.

EXHAUST AIR HEAT RECOVERY

An air-to-air heat exchanger is used to recover heat from plant exhausts. The efficiencies for varying conditions were determined and the increased fan power pressure drops were recorded.

DOMESTIC HOT WATER SYSTEM (DHW)

The DHW system is designed to recover heat from either the storage tank or the system return water whenever possible. A hydronic BTU computer monitored its output along with the electrical input. System losses and the recovery pump requirements were determined.

PROCESS FLOW

Temperatures were recorded at various points to determine the heat transfer between the process flow and the plant.

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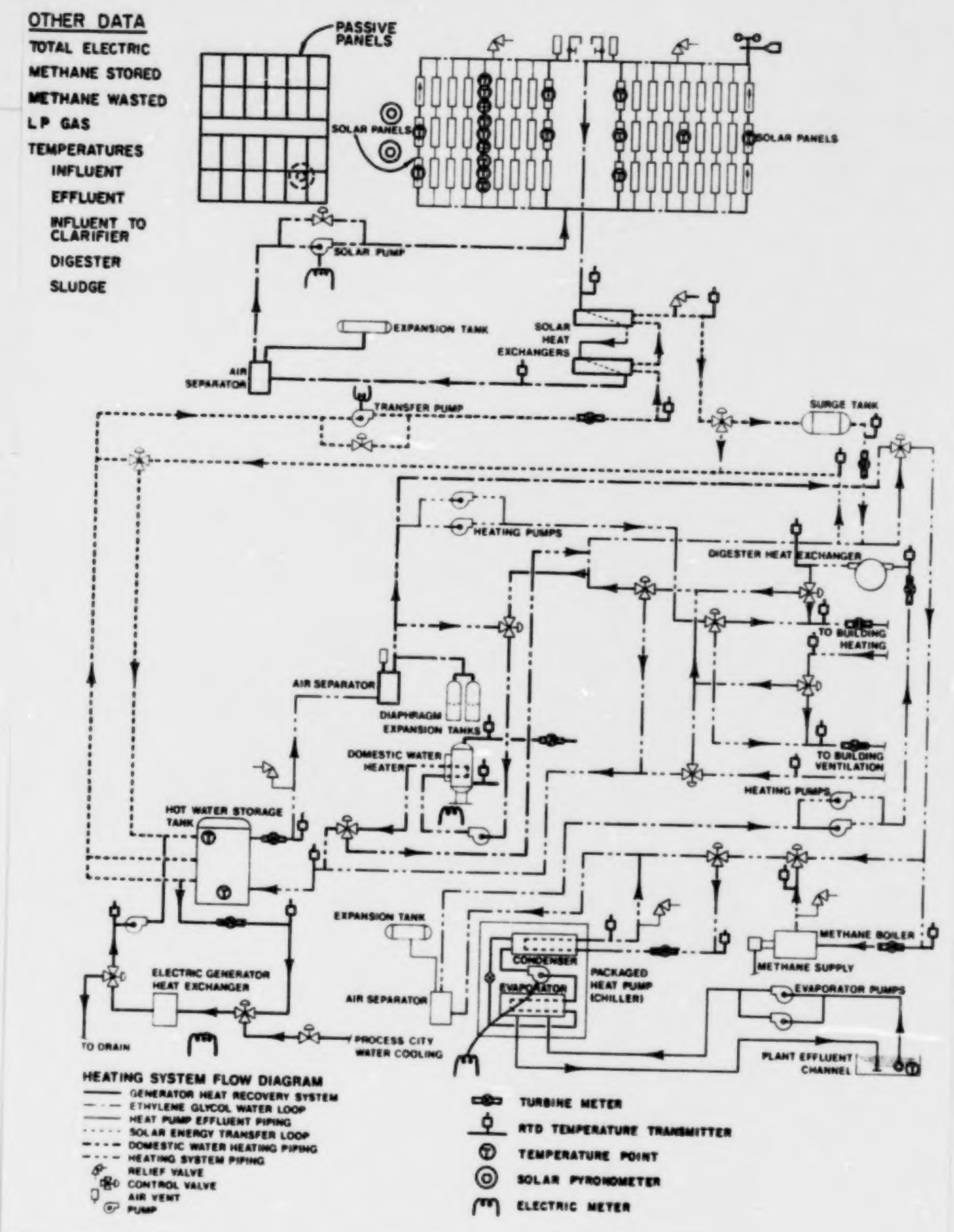
OTHER DATA
TOTAL ELECTRIC
METHANE STORED
METHANE WASTED
LP GAS
TEMPERATURES
INFLUENT
EFFLUENT
INFLUENT TO CLARIFIER
DIGESTER
SLUDGE
PASSIVE PANELS
SOLAR PANELS
SOLAR PANELS
SOLAR PUMP
EXPANSION TANK
AIR SEPARATOR
SOLAR HEAT EXCHANGERS
TRANSFER PUMP
SURGE TANK
HEATING PUMPS
DIGESTER HEAT EXCHANGER
TO BUILDING HEATING
AIR SEPARATOR
DIAPHRAGM EXPANSION TANKS
DOMESTIC WATER HEATER
TO BUILDING VENTILATION
HEATING PUMPS
HOT WATER STORAGE TANK
EXPANSION TANK
CONDENSER
EVAPORATOR
PACKAGED HEAT PUMP (CHILLER)
METHANE BOILER
METHANE SUPPLY
EVAPORATOR PUMPS
ELECTRIC GENERATOR HEAT EXCHANGER
AIR SEPARATOR
PROCESS CITY WATER COOLING
TO DRAIN
PLANT EFFLUENT CHANNEL
HEATING SYSTEM FLOW DIAGRAM
GENERATOR HEAT RECOVERY SYSTEM
ETHYLENE GLYCOL WATER LOOP
HEAT PUMP EFFLUENT PIPING
SOLAR ENERGY TRANSFER LOOP
DOMESTIC WATER HEATING PIPING
HEATING SYSTEM PIPING
RELIEF VALVE
CONTROL VALVE
AIR VENT
PUMP
TURBINE METER
RTD TEMPERATURE TRANSMITTER
TEMPERATURE POINT
SOLAR PYROMETER
ELECTRIC METER

Figure 10. Monitoring Instrumentation

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SECTION 4

PROJECTED ENERGY REQUIREMENT AND PRODUCTION

PROJECTED ENERGY REQUIREMENTS

The projected energy requirements for building heating, digester heating, and electrical equipment serve as a basis for evaluating actual performance of the respective systems. Equipment sizes, capacities, and operating schedules are described in greater detail in following sections.

Building Heating

The building heating energy requirement consists of three parts: transmission, infiltration, and ventilation. The calculation procedures to be used are those from References 3, 4 and 5. No allowance for passive solar heat gain or snow cover is taken, which is consistent with the above referenced calculation procedures.

Transmission and Infiltration

The building transmission and infiltration heat losses are calculated using the building data of Appendix B and an indoor design temperature of 13°C. To determine the monthly energy required, the Modified Degree Day Method(6) is used and then distributed on a monthly basis according to the average monthly outdoor air temperatures of Appendix C. The results are recorded in Table 3.

Ventilation Air

The building ventilation air heating requirement is calculated using the building data of Appendix B and operating schedules of Appendix D. Unit HV-2 incorporates an air-to-air heat recovery unit which provides 50 percent of the heating ventilation requirement for that unit. The average monthly outdoor air temperature is then used to estimate the monthly energy requirements as recorded in Table 3.

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Digester Heating

The anaerobic digesters convert the sludge into digester gas containing approximately 65 percent methane, 30 percent carbon dioxide, and the remainder various trace gases. The microorganisms which accomplish this require an ambient temperature of 35 ± 3°C, thus the digesters must be heated to maintain this environment.

The monthly energy requirement to maintain the digestion process is estimated for transmission losses and for sludge heating.(4)

Transmission

The digester transmission heating requirement is calculated using the building data of Appendix B and the outdoor air and groundwater temperatures* of Appendix C. At present, one digester is being operated as the primary and the other is used as an unheated secondary digester. The results of heating the primary digester are recorded in Table 3.

Sludge Heating

The sludge being pumped into the digester must be heated from the temperature of the plant influent** to the temperature of the digester. The monthly energy requirement is calculated using the ground temperatures of Appendix C and the digester system design parameters of Table 22. The results are recorded in Table 3.

Electrical Usage

The electrical requirements for the facility are based upon motor nameplate data and measured operating data. The operating schedules for each major piece of equipment appears in Appendix D. The actual measured operating amperage was used to estimate the electrical usage where available.

The electrical requirements are calculated separately for Process Equipment, Heating and Ventilating Equipment, and Lighting. The process equipment includes a wide variety of pumps, blowers, and miscellaneous equipment to ensure proper plant operation. The heating and ventilating equipment includes pumps, fans, and heaters for the building heating system, solar system, the heat pump, the emergency generator and the domestic hot water heating. The results are recorded in Table 3.

*The ground temperature is assumed to be the groundwater temperature.

**The plant influent temperature is assumed to be the ground temperature.

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TABLE 3

PROJECTED ENERGY REQUIREMENTS SUMMARY

	Bldg. Htg. (GJ)		Digester Htg. (GJ)			Electrical (kWh)			
Month	Transmission and Infiltration	Ventilation	Transmission	Make-Up Sludge	Total Heating (GJ)	Process Equipment	Heating and Ventilating Equipment	Lighting	Total Electrical
Jan.	53.35	25.50	8.51	24.92	112.28	19,860	14,560	520	34,940
Feb.	50.45	24.12	7.70	23.39	105.66	19,860	12,850	520	33,230
Mar.	36.04	17.23	7.48	24.44	85.19	19,860	10,460	520	30,840
Apr.	18.74	8.96	6.48	21.28	55.46	19,860	8,340	520	28,720
May	2.88	1.38	5.66	19.06	28.98	19,860	6,560	520	26,940
June	0	0	4.58	16.08	20.66	19,860	6,550	520	26,930
July	0	0	3.46	14.17	17.63	19,860	6,540	520	26,920
Aug.	0	0	4.18	13.68	17.86	19,860	6,540	520	26,920
Sept.	0	0	4.63	14.19	18.82	19,860	6,540	520	26,920
Oct.	10.09	4.82	5.71	17.10	37.72	19,860	6,550	520	26,930
Nov.	25.96	12.41	6.53	19.39	64.29	19,860	9,370	520	29,750
Dec.	36.04	17.23	7.54	22.97	83.78	19,860	11,710	520	32,090
ANNUAL	233.55	111.65	72.46	230.67	648.33	238,320	106,570	6,240	351,130

PROJECTED ENERGY PRODUCTION

The energy produced by the various sources, including the active and passive solar, the gas boiler, the heat pump, and the generator heat recovery can be estimated from design performance criteria. These projected energy source contributions will then serve as a basis for evaluating actual performance of the respective systems.

Passive Solar

The passive solar array consists of 83 m^2 of panels with an effective collection area of 75 m^2 facing 2° west of south at an angle of 60° from the horizontal. The transmissivity is listed as 66% in the manufacturer's literature.

The heating energy supplied by the passive solar system is estimated by using the estimated incident solar insolation of Table 5, a cloud cover factor from Appendix F (Albany, New York), a transmissivity of 66%, and an overhang shading factor from Appendix L.

The heat provided by the passive array is usable in the Clarifier Room only. The net contribution of the passive system is determined in Table 4 below, and transferred to Table 8.

TABLE 4

NET PASSIVE SOLAR CONTRIBUTION

Month	Design Heat Loss Monthly (GJ)	Passive Solar Collected (GJ)	Net Passive Solar Contribution (GJ)
J	19.7	12.5	12.5
F	18.0	15.6	15.6
M	13.9	18.6	13.9
A	7.0	16.5	7.0
M	0	15.5	0
J	0	15.2	0
J	0	16.2	0
A	0	18.0	0
S	0	18.5	0
O	2.2	18.1	2.2
N	8.4	11.7	8.4
D	13.3	10.0	10.0

Active Solar

The active solar array consists of 54 double-glazed panels with an effective collection area of 119.5 m² facing 2° west of south at an angle of 60° from the horizontal.

The specification and installation details are described in greater detail in Appendix M.

The heating energy supplied by the active solar system is estimated by the manufacturer in the Tables 5 and 6, and a cloud cover factor from Appendix F (Albany, New York). Since the heating provided by the active solar system is useful only when such heating is required, the net active solar contribution is determined in Table 7 below, and transferred to Table 8.

TABLE 5

NET ACTIVE SOLAR CONTRIBUTION

Month	Total Heating Requirement Remaining after Passive Solar Contrib. (GJ)	Available Active Solar Energy (GJ)	Net Active Solar Contribution (GJ)
J	103.10	10.23	10.23
F	90.05	14.60	14.60
M	71.26	17.74	17.74
A	48.49	15.64	15.64
M	28.97	15.14	15.14
J	20.66	14.90	14.90
J	17.63	17.12	17.12
A	17.86	19.50	17.86
S	18.82	19.97	18.82
O	35.50	19.26	19.26
N	55.85	10.98	10.98
D	73.76	8.18	8.18

TABLE 6

ESTIMATED INCIDENT SOLAR ENERGY ON ARRAY - W/m^2

LOCAL SOLAR TIME 15th DAY OF MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
8 am	92.7	289.1	354.7	343.9	314.3	296.0	300.7	323.1	338.9	309.9	175.9	31.5
9	452.1	565.2	592.4	555.5	505.7	475.1	481.1	518.0	556.1	559.6	490.8	590.8
10	689.8	774.6	785.3	730.4	663.9	623.9	631.1	679.4	734.5	267.4	712.5	650.0
11	836.4	912.3	915.5	849.9	773.0	726.0	734.2	790.0	856.2	887.7	853.4	799.5
12 pm	896.3	971.3	972.9	903.2	821.5	772.0	780.2	839.5	909.8	944.8	912.0	859.7
1	867.2	947.3	952.4	885.2	805.8	757.2	765.1	822.8	890.6	922.1	885.2	828.8
2	744.9	839.5	854.3	797.3	726.3	683.1	689.1	741.1	799.2	820.3	769.8	701.4
3	514.5	647.8	684.1	645.9	590.8	556.1	561.8	601.5	642.2	641.8	559.6	456.2
4	114.4	361.6	451.4	445.4	411.7	389.3	393.4	417.7	431.3	389.0	217.8	38.8
TOTALS	5208	6308	6563	6157	5615	5280	5337	5734	6160	6232	5577	4767

TABLE 7

ESTIMATED NET ENERGY COLLECTION OF SOLAR ARRAY - kW

LOCAL SOLAR TIME 15th DAY OF MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
8 am	0	0	0	0	0	0	0	0	0	0	0	0
9	2.9	12.5	16.8	15.4	13.6	12.2	15.0	18.9	20.8	19.5	10.6	0
10	26.7	34.5	37.3	33.6	29.4	27.8	30.3	35.4	39.5	40.3	33.1	0
11	43.0	50.4	52.5	47.2	41.4	38.7	41.4	47.8	53.6	55.6	49.1	24.1
12 pm	50.2	57.7	59.6	53.6	47.0	43.9	46.7	53.7	60.2	62.7	56.2	40.5
1	47.0	55.0	57.3	51.6	45.3	42.3	45.0	51.8	58.0	60.1	53.3	47.6
2	33.5	42.5	45.7	41.4	36.4	34.2	36.8	42.5	47.3	48.2	40.3	44.3
3	10.0	21.7	26.8	25.0	22.1	21.2	23.6	27.6	30.1	28.7	18.3	30.4
4	0	0	3.9	5.3	2.8	2.3	4.7	8.6	9.4	4.2	0	5.9
TOTALS	213	274	300	273	238	222	244	286	319	319	261	193

TABLE 8. PROJECTED HEATING ENERGY SOURCES (GJ)

Month	Passive Solar Contribution	Active Solar Contribution	Emergency Generator Contribution	Methane Boiler Contribution	Heat Pump Contribution	Total Heating Contribution
January	12.5	10.23	1.2	15.25	73.19	112.37
February	15.6	14.60	1.2	14.13	60.16	105.69
March	13.9	17.74	1.2	15.25	37.12	85.21
April	7.0	15.64	1.2	14.69	17.01	55.54
May	0	15.14	1.2	12.67	0	29.01
June	0	14.90	1.2	4.60	0	20.70
July	0	17.12	0.5	0	0	17.62
August	0	17.86	0	0	0	17.86
September	0	18.82	0	0	0	18.82
October	2.2	19.26	1.2	15.09	0	37.75
November	8.4	10.98	1.2	16.71	26.99	64.28
December	10.0	8.18	1.2	15.25	49.18	83.81
ANNUAL	69.6	180.47	11.3	123.64	263.65	648.66

Emergency Generator

The emergency generator set provides electrical power to the facility during an electrical power outage. Specification details can be found in Appendix I. The fuel available to the generator is plant methane or propane, depending upon the quantity of methane which has been stored. The generator is cooled with the building heating system water, thereby extracting the otherwise wasted energy of the generator cooling system. During normal operation the generator is exercised once a week for an average of 60 minutes.

For estimation purposes the electrical conversion efficiency of the generator and the heat recovery efficiency will be taken as 25% and 50% respectively. From the electrical usage data presented earlier, the average electrical power required during the exercise period will be taken as 40kW. The monthly contribution to the building heating requirement is summarized in Table 8. When no building heating is required, the generator is cooled by city water and the cooling water heating energy is not recovered.

Gas Boiler

The gas boiler uses digester gas to provide additional heating energy when that supplied by the solar systems is less than that required by the building. The methane gas used is that which has been collected, compressed, and stored in the high pressure storage tanks. The gas is stored in two 3.8 m^3 tanks at a maximum pressure of 1.38 MPa.

The quantity of digester gas which should be produced was estimated at 47 m^3/day with a heating value of 22,400 kJ/m^3. The usable storage capacity is then 113 m^3 @ 1.38 MPa with a total heating value of 2.5 GJ. This is a storage capacity of 3 days' gas production.

To estimate the monthly heating contribution of the gas boiler, a combustion efficiency of 80% is used. Also, during the months when the boiler does not require all the methane which is produced, the remainder will be assumed to be stored in the high pressure tanks up to a usable maximum of 113 m^3 and used at a later date. The monthly contribution is summarized in Table 8. See Appendix I for boiler specifications.

Heat Pump

The heat pump provides additional heating energy when that supplied by the solar systems is less than that required by the building and digester gas is not available for the boiler. Specifications for the heat pump are listed in Appendix I.

For estimation purposes, the difference between the total heating requirements of Table 8 and all other heating sources is taken as that to be supplied by the heat pump.

Summary

From Table 8 the monthly and annual percent contribution of each heating source can be determined. These percentages are listed in Table 9 below.

TABLE 9. PERCENT ENERGY SOURCE CONTRIBUTION FOR HEATING

Month	Passive Solar	Active Solar	Emergency Generator	Methane Boiler	Heat Pump
J	11	9	1	14	65
F	15	14	1	13	57
M	16	21	2	18	43
A	13	28	2	27	31
M	0	52	4	44	0
J	0	72	6	22	0
J	0	97	3	0	0
A	0	100	0	0	0
S	0	100	0	0	0
O	6	51	3	40	0
N	13	17	2	26	42
D	12	10	1	18	59
ANNUAL	11	28	2	19	40

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SECTION 5

ACTUAL ENERGY REQUIREMENT AND PRODUCTION

The data for the energy monitoring system were generally collected once a day at 7:00 am. However, on occasion, the recording times varied and at times data were lost due to power failure at the facility. See Chapter 7 for further details. Also, in the data collection routine, there is an element of possible human error and/or imprecision. For each month, generally only a few days' data have been lost to such problems. The data presented in Table 12 represents the energy usage for the entire month. The days with no data are included at the average of those days of the month with valid data.

All data for all users were monitored at the point of use, thus distribution losses will not be included in the energy requirements, but will be reflected in the difference between the energy required and energy produced.

ACTUAL ENERGY REQUIREMENTS

The results from the monitoring system data are presented for the building heating, digester heating and electrical systems. These results are then compared with the projections of Chapter 4.

The energy users include the building heating, digester, domestic hot water, HV-1, HV-2, and all electrical equipment. The individual usage of each and the total of all users are listed in Table 12.

Digester

The heating requirement of the digestion process is a significant portion of the total requirement of the facility. The monitoring data are presented in Table 10 and Table 12. These monthly figures represent both transmission losses of the digester and sludge heating. Also listed are the monthly projected heating requirements for the digestion process heating from Table 3 as a comparison.

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The actual digester heating varied considerably from the projections between June and September. This is due basically to operational and instrumentation problems encountered during startup and testing of the various systems (See Chapter 7). After August most of these problems were corrected and the actual performance stabilized and closely matched the projected performance. Once the process is optimized, the actual requirements should be significantly lower than projected.

TABLE 10. DIGESTER HEATING SUMMARY

	Digester Heating Requirements (GJ)		Total Heating* Requirements (GJ)		Percentage of Digester Heat to Total	
Month	Projected Table 3	Actual	Projected Table 3	Actual Produced	Projected	Actual
J	33.43	33.531	112.28	102.622	30	33
F	31.09	22.917	105.66	93.960	29	24
M	31.92	33.624	85.19	92.891	37	36
A	27.76	--	55.46	--	50	--
M	24.72	--	28.98	--	85	--
J	20.66	9.774	20.66	18.137	100	54
J	17.63	7.603	17.63	10.977	100	69
A	17.86	11.561	17.86	17.522	100	66
S	18.82	19.107	18.82	29.672	100	64
O	22.81	22.335	37.72	47.555	60	47
N	25.92	21.177	64.29	48.080	40	44
D	30.51	31.363	83.78	88.393	36	35
Annual	303.13	265.463**	648.33	634.242**	47	51*

*Total Heating includes the digester and building loads

**Using projected figures for April and May

Domestic Hot Water

The monitoring on the domestic hot water system indicates that usage has been steadily increasing during the year. This is due to increased laboratory work required as the plant becomes fully operational, plus a temporary increase in the number of full-time employees from two to three. Additionally, the temperature of the water was raised on occasion, increasing heat consumption, though not water usage. The summary of the domestic hot water usage is given in Table 12.

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)

PAGE NUMBER

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TYPING GUIDE SHEET

Building Heating

The building heating loop includes all unit heaters, cabinet unit heaters, etc., heating the building. Due to temperature transmitter setpoint drift (see Chapter 7), this monitoring point was not operational until March. Thus the data presented in Table 12 indicate estimated energy usage based on the data recorded from March 1 to March 26 and weighted with the monthly OA temperature actually experienced and an indoor temperature of 13°C (the value used was 8,100 W/°K).

Heating and Ventilating Unit HV-1

A persistent automatic low temperature cutout problem was experienced on HV-1 during the winter which was attributable to temperature transmitter setpoint drift (see Chapter 7). The situation has now been corrected. The monitoring data, however, is still valid, but does not represent what the total heating requirement at this unit would have been. But for purposes here, the data are valid as far as the energy actually required during the year. Table 12 summarizes the data on HV-1.

Heating and Ventilating Unit HV-2

Some of the monitoring equipment on HV-2 was found to be improperly applied and was replaced. No data can be considered valid for this unit during the monitoring period reported here. Thus, for purposes here, estimates are made on the heating energy which would have been required by this unit. This unit incorporated an air-to-air heat recovery unit which has been tested several times to determine its performance. No continuous monitoring equipment was applied to this unit.

The heating required for HV-2 to heat the outside air to 13°C was estimated using the average monthly outside air temperatures of Appendix C. Estimates for the heating and electrical requirements were made both with and without the heat exchanger. These estimates can then be used to evaluate the annual performance. The thermal efficiency of the heat exchanger was taken as 67% from Appendix J. The increase in pressure requirements on the two fan motors (HV-2 and EF-4) were also included in Appendix J and the increase in the electrical energy requirements was then estimated from the fan manufacturer's literature.

The results of all these calculations are summarized in Table 11.

ACTUAL ENERGY PRODUCTION

The results of the monitoring system data are presented for the active and passive solar, heat pump, methane boiler, generator, and domestic hot water (electrical) systems. These results are compared with the projections of Chapter 4. Each system was analyzed and the results listed in Table 12 as the total net system contribution as a source of energy.

TABLE 11 AIR-TO-AIR HEAT EXCHANGER SUMMARY

MONTH	OPERATING HRS.	HV-2 /EF-4 m³/s of OA*	OAT** (°C)	HEATING ENERGY REQUIREMENTS (GJ)		HV-2 ELECTRICAL ENERGY REQUIREMENTS (1)						EF-4 ELECTRICAL ENERGY REQUIREMENTS (1)					
				WITHOUT Z-DUCT	WITH Z-DUCT (SEE APPENDIX J)	WITHOUT Z-DUCT			WITH Z-DUCT			WITHOUT Z-DUCT			WITH Z-DUCT		
						TSP	KW	KWH	TSP	W	KWH	TSP	KW	KWH	TSP	KW	KWH
JAN.	177	1.23	7	18.51	6.11	1.23	0.77	170	2.10	1.07	238	1.0	0.89	196	1.5	1.27	281
FEB.	157		8	17.36	5.73			151			211			174			249
MAR.	177		1	13.22	4.36			170			238			196			281
APR.	171		(5)[2]	(7.15)[2]	(2.36)[2]			164			230			190			271
MAY	177		(11)[2]	(1.58)[2]	(0.53)[2]			170			238			196			281
JUN.	171		17	0	0			164			230			190			271
JUL.	177		22	0	0			170			238			196			281
AUG.	177		17	0	0			170			238			196			281
SEPT.	171		12	0.51	0.17			164			230			190			271
OCT.	177		8	4.76	1.57			170			238			196			281
NOV.	171		4	7.66	2.53			164			230			190			271
DEC.	177	▼	4	15.87	5.23	▼	▼	170	▼	▼	238	▼	▼	196	▼	▼	281
ANNUAL	2080			86.62	28.59			1997			2797			2306			3300
ENERGY SAVINGS					58.03												
ENERGY INPUT											800						994

(1) FROM MANUFACTURER'S LITERATURE

(2) ANTICIPATED ACTUAL AVERAGE MONTHLY TEMPERATURES. FROM JUNE 79 TO MAR 80, THE ORIGINAL PROJECTED OA TEMPERATURES ARE 1° WARMER, ON THE 10 MONTH AVERAGE, THAN THE ACTUAL MEASURED TEMPERATURE.

* OA: OUTSIDE AIR

** OAT: OUTSIDE AIR TEMPERATURE

TABLE 12

ENERGY CONTRIBUTION SUMMARY - USERS AND PRODUCERS (GJ)

USERS	JUNE	JULY	AUGUST	SEPT	OCT	NOV	DEC	JAN	FEB	MARCH
Digester	9.774	7.603	11.561	19.107	22.335	21.177	31.363	33.531	22.917	33.624
DHW	0.534	0.109	0.101	0.085	0.616	0.593	1.837	2.405	5.021	2.089
BLDG. HTG. (5)	0	0	0	0	0.51	7.14	14.88	17.80	18.14	12.794
HV-1	0.022	0.033	0.030	0.059	0.531	1.551	8.729 5.09^3	11.644 7.10^3	7.092 5.05^3	6.556 3.25^3
HV-2	0.210^1	0.024^1	0	0.264^2	2.47^2	3.98^2	8.21^2	9.58^2	9.47^2	6.844^2
TOTAL	10.540	7.769	11.692	19.515	26.462	34.441	70.109	82.06	67.690	65.157
PRODUCERS										
ACTIVE SOLAR	10.315	8.932	12.907	25.821	10.663	8.225	11.341	7.453	13.254	14.067
PASSIVE SOLAR (4)	0	0	0	0	2.93	6.82	10.08	11.27	13.41	11.07
GENERATOR	0.327	1.047	0.445	0.457	0.345	0.548	1.192	1.065	1.333	1.665
BOILER	5.760	0.007	0.020	0	0.045	0	12.053	8.292	0.007	0.017
HEAT PUMP	0.559	0.005	3.784	3.057	32.594	31.653	52.778	73.548	64.159	64.728
DHW (ELEC)	1.176	0.985	0.366	0.375	0.975	0.839	0.952	0.996	1.797	1.346
TOTAL	18.137	10.976	17.522	29.710	47.552	48.085	88.396	102.624	93.960	92.893

(1) BTU meter
(2) Estimated value used from ventilation requirements.
(3) Additional required from passive solar section
(4) From passive section
(5) Estimated value from march data. Tank temperature setting wrong (drifted).

Passive Solar

The passive solar panels located in the Clarifier Room are constructed of four layers of translucent fiberglass sheeting with aluminum bracing. According to the manufacturer, the U factor is 1.65 W/m² °K and the transmissivity is 66%. The total area is 83 m² with an effective light transmissive area (aperature) of 75 m². The panels are facing 2 degrees west of south at an angle of 60 degrees to the horizontal. A building overhang provides partial shading in the summer and allows for full exposure in the winter, thereby aiding in summer cooling and winter heating. To further aid in winter heating, the building is designed such that light reflected from the snow cover is directed to the passive array.

The panels were evaluated according to solar transmissivity, energy effectiveness, overall collector performance, durability, and practicality.

Solar Transmissivity

The transmissivity of the panels was monitored by using pyronometers on either side of the panels and measuring both the incident and the transmitted solar radiation. The peak hourly and average daily transmissivity are recorded in Table 13.

The peak noon time transmissivity ranged from 35% in July to 57% in January. Part of this reduction from the 66% estimated transmissivity is due to the overhang. The remainder of the reduction is obviously due to other factors such as dust on the panels and surface reflection due to the sun-panel angle.

Energy Effectiveness

The energy effectiveness of the passive array in the Clarifier Room is estimated using building and weather design data and then comparing the estimate with actual data collected by the energy monitoring system. The estimated energy usage is based on the building data of Appendix B, the actual weather data of Appendix C, and a Clarifier Room temperature of 13°C. The actual energy usage is based on the same building data and weather data, but also on the actual Clarifier Room temperature and the solar radiation transmitted through the panels as determined in the previous section. The total passive solar energy contribution is then determined, and the additional heating required is calculated.

The energy usage is then estimated for the Clarifier Room were the passive array replaced with a block wall. All the energy then required would be supplied by the building heating source. The difference between the additional heating energy required with the passive panels and the heating energy required without them is a measure of the energy effectiveness of the passive panels.

Table 14 summarizes these data.

Overall Evaluation

The passive array was also studied to determine:

1. Lighting energy contribution
2. Utilization of the material as a wall surface
3. Durability

1. Lighting Energy Contribution

The lighting levels during the day light hours are generally sufficient to operate the facility.

2. Utilization of the Material as Wall Surface

The material as a wall surface has now been installed for a period of about four years. Minor intermittent condensation has been observed within the layers of transparent panels. This is considered normal for such units. The moisture does not appear to have a cumulative effect. Leaks have occurred in the weep holes and the perimeter framing. Both conditions have been attributed to the sixty degree slope of the glazed surface. Removal and reinstallation have corrected the leaking. A slight yellow discoloring of exterior surface areas has been observed.

3. Durability

The longevity, stability and consistent performance of the materials in the wall appear to be unchanged since installation with the exception of a slight yellow discoloring of the exterior surface. It appears to be a photo reaction of the film coating.

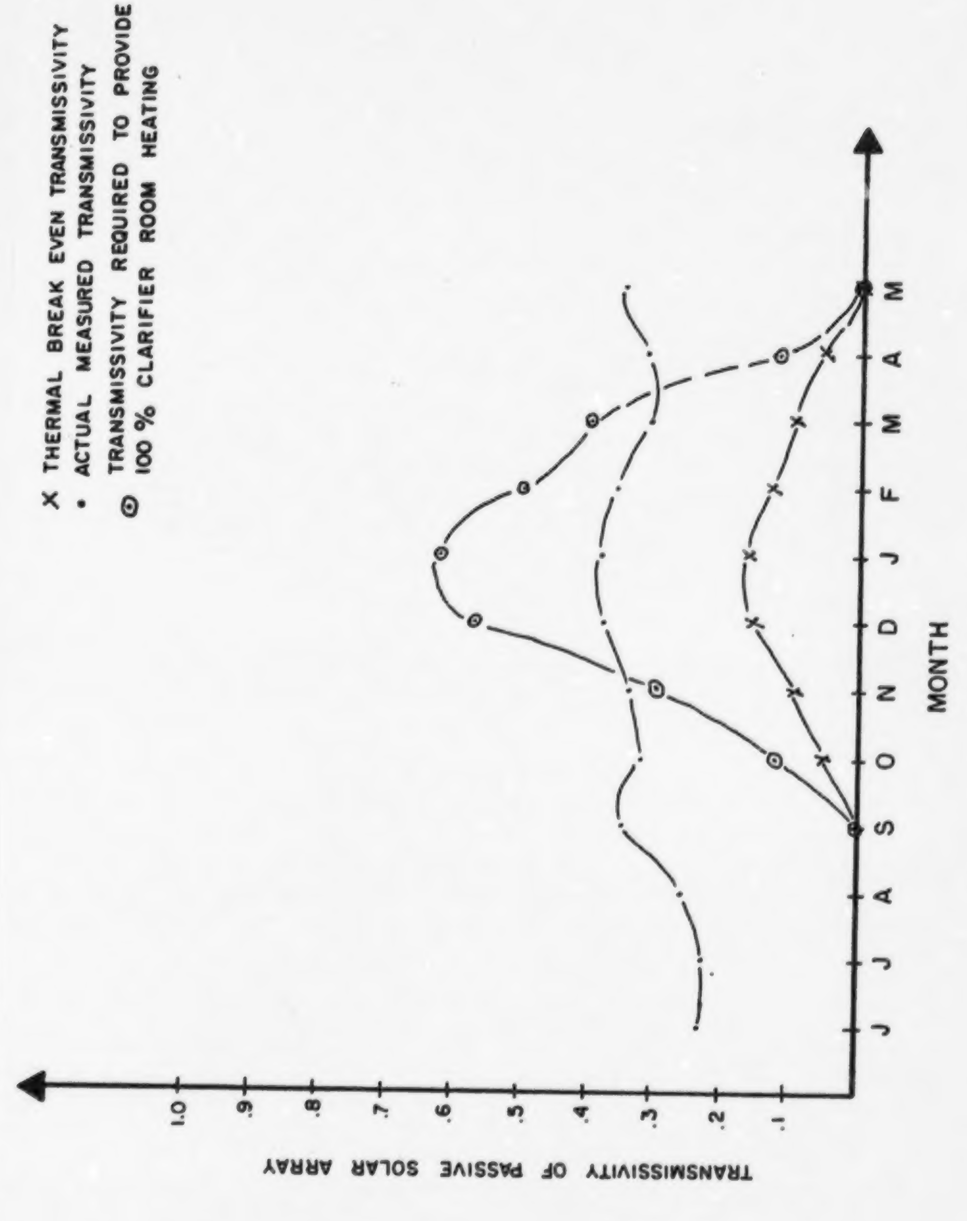

FIGURE 11
PASSIVE PANEL TRANSMISSIVITY

TABLE 13

PASSIVE COLLECTOR TRANSMISSIVITY

	ANTICIPATED *				MEASURED **					
	INCIDENT INSOLATION		TRANSMISSIVITY***		INCIDENT INSOLATION		TRANSMISSIVITY			
Month	Peak Noon (W/m^2)	Avg. (W/m^2)	Peak Noon ($W/^2m$)	Ave. (W/m^2)	Peak Noon ($W/^2m$)	Avg. (W/m^2)	Peak Noon (W/m^2)	%	Avg. (W/m^2)	%
J	896	93	591	62	1,062	147	602	57	56	38
F	942	130	622	86	1,017	195	574	56	71	36
M	934	139	617	92	1,119	175	573	51	54	31
A	849	128	561	84	--	--	--	--	--	--
M	715	116	472	77	--	--	--	--	--	--
J	664	117	438	77	687	170	309	45	40	23
J	679	122	448	80	728	175	252	35	40	23
A	781	136	515	89	882	165	460	52	42	26
S	874	143	577	94	965	222	504	52	79	35
O	916	136	605	90	990	121	545	55	38	32
N	912	92	602	61	993	114	558	56	38	34
D	860	75	568	50	1034	133	558	54	50	38

* Solar Data from Table 5, Appendix L and Appendix F

** See Appendix L for overhang correction factors

*** From Manufacturer's Data (66%)

Table 14

PASSIVE SOLAR ENERGY PERFORMANCE

Month	Design Heat Loss * Clarifier Room with Passive Array (GJ)	Actual Passive Energy Collected (GJ)	Net Passive Solar Energy Contribution (GJ)	Additional Heating Required (GJ)	Design Heat Loss ** Clarifier Room without Passive Array (GJ)
January	-18.37	11.27	11.27	7.10	-13.33
February	-18.46	13.41	13.41	5.05	-13.48
March	-14.32	11.07	11.07	3.25	-10.72
April	-	-	-	-	-
May	-	-	-	-	-
June	0	7.80	0	0	0
July	0	8.04	0	0	0
August	0	8.54	0	0	0
September	0	15.39	0	0	0
October	-2.93	7.78	2.93	0	-1.64
November	-6.82	7.49	6.82	0	-4.73
December	-15.16	10.08	10.08	5.08	-10.84
TOTAL	-76.08	100.87	55.58	20.48	-54.74

* Clarifier room heat loss using an inside temperature of 13°C and actual OAT and GWT.

** Clarifier room heat loss substituting an insulated masonry wall for the passive array.

Active Solar

The active solar energy system is the primary source of heating energy for the building. When heating is required and the solar system is operating, the other sources provide supplemental heating as required. When heating is not required and the solar system is operating, the storage tank is heated for later use. The anticipated operating conditions and physical arrangement are described in Chapter 4.

The available insolation is measured as a reference by which to evaluate actual collector and system performance. The percentage of insolation attributable to reflection is also determined by use of a shielded pyronometer which eliminates the reflected component.

Insolation

The available insolation is the total solar radiation incident on the collectors including reflected radiation. Table 15 below summarizes the measured peak noon isolation and daily average isolation and lists comparable estimated values used for design.

TABLE 15. ESTIMATED AND MEASURED INSOLATION FOR WILTON, ME.

	Peak Noon (W/m^2)			Average Daily (W/m^2)		
Month	Estimated*	Measured	% of Est	Estimated*	Measured	% of Est
J	895	1,050	117	93	149	160
F	971	1,034	106	134	198	148
M	974	1,132	116	145	172	119
A	--	--	--	--	--	--
M	--	--	--	--	--	--
J	772	798	103	136	191	140
J	782	826	106	140	198	141
A	839	936	112	146	172	118
S	911	980	108	149	228	153
O	946	1,006	106	140	123	87
N	911	980	108	91	112	124
D	861	1,021	119	76	137	181

* From Table 5 and Appendix F (Albany, New York)

The increase in incident solar radiation due to reflection from the ground was determined using two pyronometers. One pyronometer measured the total incident insolation and one measured the total incident insolation minus ground reflectance. To accomplish this a shield was placed on one pyronometer which shades it from all incoming radiation below the horizon.

The design of the building and location of both the active and passive solar panels is such that sunlight will be reflected off snow covered ground onto the arrays, thereby increasing the amount of solar radiation available for collection or transmittance.

During the winter, snow cover should increase the reflected radiation, but during the winter of 1979-1980 the ground was seldom covered by any appreciable amount of snow. It was also found that during the spring and summer rainshowers, the shielded pyronometer sometimes read higher than the unshielded due to reflections by the wet shield. This is not considered important because the reflected radiation we are most concerned with is that reflected during the winter heating season.

Due to the minimal snow cover experienced, it is difficult to accurately assess any increase in reflected energy due to the landscaping. On the contrary, there appeared to be no significant increase.

Table 16 summarizes the average monthly incident insolation for both the shielded and unshielded pyronometers and the percent difference between the two.

Collector Efficiency

The instantaneous collector efficiency was determined using the data which has been collected and compared with the anticipated performance of Figure 12. Table 17 summarizes the data relevant to the calculation procedure. Figure 13 is the collector efficiency versus temperature-insolation parameter graph for the recorded data.

The following example illustrates the use of data in Table 17 in the calculation of collector efficiency:

$$\text{Efficiency} = \frac{\text{Heat Removed from Collectors}}{\text{(Effective Area of Collectors) (Solar Insolation)}} \times 100\%$$

$$\frac{\text{Heat Removed}}{\text{Effective Area}} = \text{(Flow Rate per Unit Area)} \times \text{(Fluid Specific Heat)} \times \text{(Fluid Density)} \times (T_{out} - T_{in})$$

TABLE 16

SHIELDED/UNSHIELDED INSOLATION

Month	Peak Noon (W/m²)			Average Daily (W/m²)		
	Unshielded	Shielded	% Difference*	Unshielded	Shielded	% Difference**
J	1,050	1,021	3	149	129	14
F	1,034	1,021	1	198	175	12
M	1,132	1,062	6	172	146	16
A	--	--	--	--	--	--
M	--	--	--	--	--	--
J	798	798	0	191	165	14
J	826	810	2	198	165	17
A	936	936	0	172	142	17
S	980	980	0	228	207	9
O	1,006	1,006	0	123	105	14
N	980	980	0	112	97	13
D	1,021	936	8	137	123	10

* Data is within the limits of the instrumentation accuracy.

** Data actually includes both reflected and diffuse energy which has been shielded.

From Table 17, January 6 Data:

$$\frac{\text{Heat Removed}}{\text{Effective Area}} = \left(2{,}139 \times 10^{-5}\ \frac{m^3}{5\ m^2}\right) \times \left(3849\ \frac{J}{kg\ {}^\circ K}\right) \times \left(1028\ \frac{kg}{m^3}\right) \times$$

$$(54.3^\circ C - 48.8^\circ C) \times \frac{(1^\circ K)}{1^\circ C} \times \frac{(1\ WS)}{1J} = 465.5\ \frac{W}{m^2}$$

$$\text{Efficiency} = \frac{465.5\ \frac{W}{m^2}}{839.2\ \frac{W}{m^2}} \times 100\% = 55\%$$

All calculations use the effective collector area (119.4 m^2) and total measured insolation data. Generally, a minimum of one day per month was selected where the sky was relatively clear, thereby eliminating cloud cover reductions in performance. The next section of this report addresses the collector efficiency for average daily conditions which include cloud cover, rain, snow, etc. Also, days were selected which would be useful in evaluating the performance of the collectors due to the glycol percentage being used.

From Figure 13 it can be seen that there is some scattering of the data points. Generally, the points have been below the minimum performance line for fifty percent glycol solution and on the line for zero and thirty percent glycol. Several explanations are possible to explain this scattering of the data points: transitional glycol flow (turbulent-laminar), glycol percentage (variable fluid properties), wind, air within the fluid loop, conduction losses between the collector and structural supports, convection losses between the absorber plate and the rigid insulation, and reflection.

The transport phenomenon of transition from laminar to turbulent flow occurs, it is generally agreed, from between Reynolds numbers of 2,000 to 4,000.

From Table 17, the Reynolds numbers are generally within the transitional phase of fluid flow. When in this range, the flow can be either turbulent or laminar with the associated variation in heat transfer properties.

The percentage of glycol in the collector fluid has been varied in an attempt to determine the affect on collector performance. No consistent, reliable trends were discovered. This is generally due to lack of valid monitored data points and the significant scattering of the points.

The effects of wind speed and direction and reflected solar energy on collector performance appear to be insignificant.

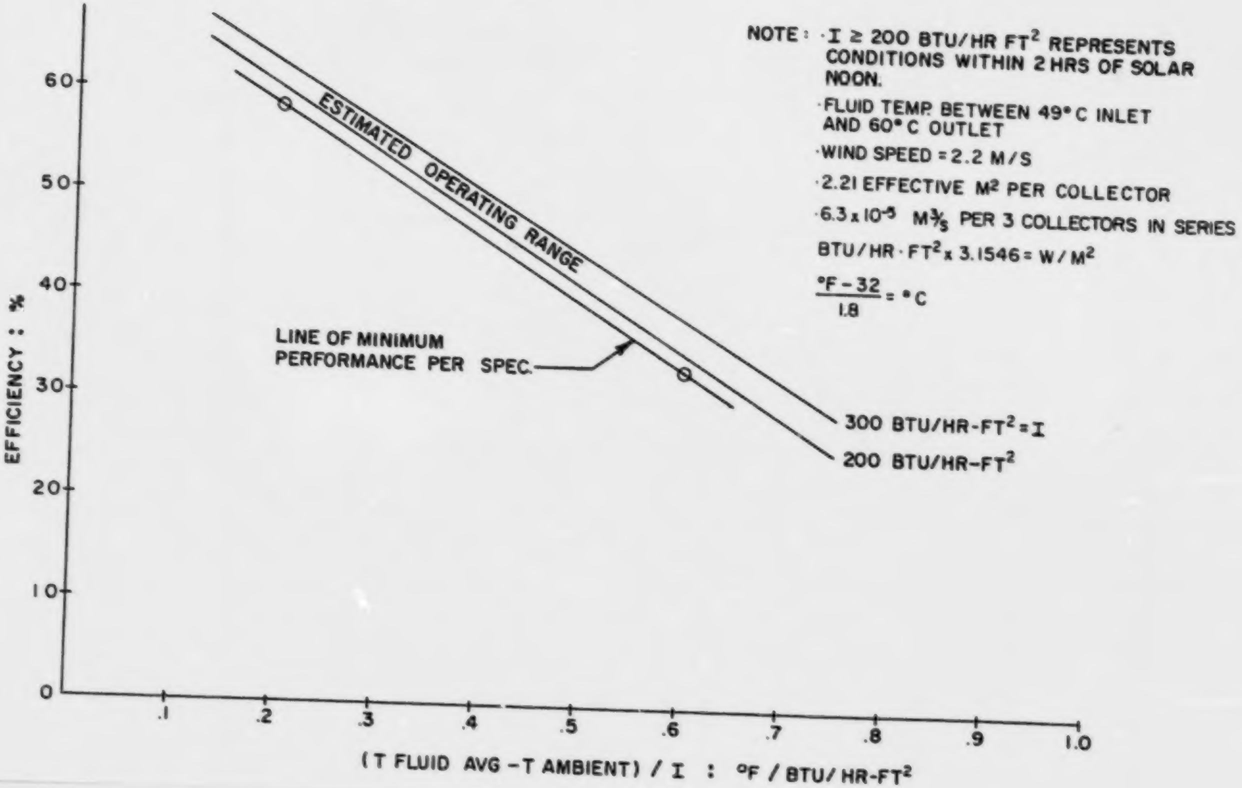

Figure 12. Collector Performance Curve (Predicted) - Grumman Model 210F Collector

TABLE 17

COLLECTOR PERFORMANCE DATA

MONTH	DAY	TIME	% GLYCOL BY WEIGHT	GLYCOL TEMP°C		COLLECTOR FLUID FLOW $m^3/s \cdot m^2 \times 10^{-5}$	SPECIFIC HEAT J/Kg.K	DENSITY Kg/m^3	VISCOSITY Pa.sx 10^{-6}	TUBE VELOCITY m/s	REYNOLDS NUMBER	OA TEMP. °C	INSOLATION w/m^2	EFFICIENCY %	
				IN	OUT									FIGURE 12	ACTUAL
JAN	6	12N to 2PM	30 *	48.8	54.3	2.139 *	3849	1028	1003	0.187	2432	-4.8	839.2	51	55
FEB	10	12N to 2PM	50 *	47.8	54.5	2.073 *	3515	1052	1699	0.181	1423	-3.5	965.6	55	53
	20	1PM to 3PM	50 *	51.0	57.2	2.075 *	3556	1050	1600	0.181	1509	8.6	777.7	53	62
MAR	16	12N to 2PM	50 *	54.7	60.3	2.034	3598	1048	1500	0.178	1577	0.	1012.9	56	43
	23	11AM to 1PM	50 *	49.6	58.2	2.073	3556	1050	1600	0.181	1509	9.2	1004.7	60	66
JUN	26	12N to 2PM	50	53.1	57.1	2.139 **	3556	1050	1600	0.187	1557	22.9	776.8	59	41
JUL	8	12N to 2PM	50	45.0	50.5	2.139 *	3515	1055	1699	0.187	1473	28.8	729.5	64	60
AUG	9	12N to 2PM	50	51.8	56.8	2.139 *	3556	1050	1801	0.187	1383	20.8	878.9	61	46
	22	1PM to 3PM	0	50.7	55.5	2.192 **	4184	986	518	0.191	4627	24.5	741.5	60	59
	30	12N to 2PM	0	43.7	47.8	2.192 *	4184	990	586	0.191	4105	27.2	908.9	65	41
SEPT	7	12N to 2PM	0	46.3	52.3	2.192 *	4184	989	546	0.191	4401	21.6	897.8	64	61
	18	12N to 2PM	0	45.9	52.4	2.192 *	4184	989	546	0.191	4401	23.7	924.9	65	64
OCT	18	12N to 2PM	30	49.3	55.6	2.139 **	3849	1028	1003	0.187	2432	11.8	953.0	60	55
NOV	1	11AM to 1 PM	30	45.3	51.1	2.139 *	3849	1029	1103	0.187	2214	12.8	972.9	62	52**
	15	10AM to 12N	30	45.9	51.2	2.139 *	3849	1029	1105	0.187	2214	1.8	943.2	58	47
DEC	21	12N to 2PM	30	47.2	52.0	2.139 *	3849	1029	1103	0.187	2214	-8.0	784.7	48	52

* Estimated ** From Motor Readings

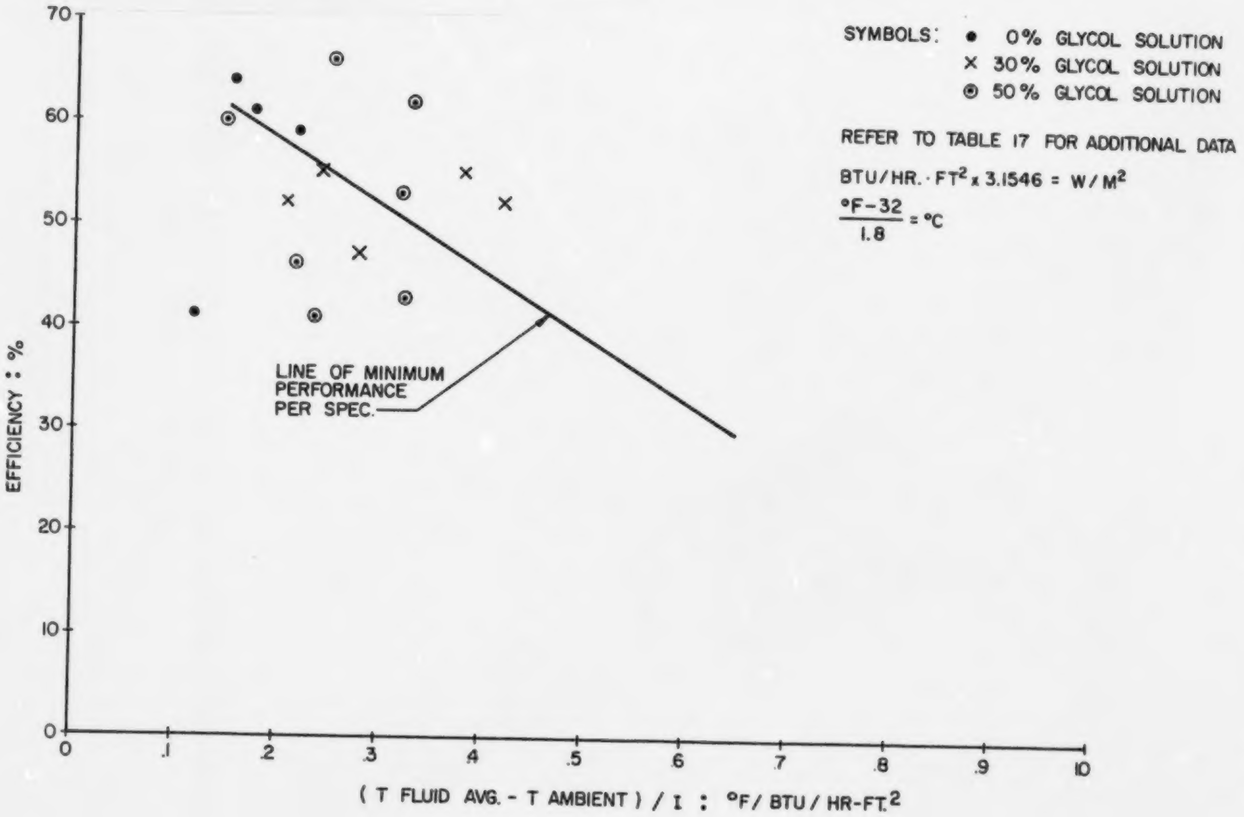

Figure 13. Collector Performance Curve (Acual) - Grumman Model 201 Collector

Active Solar System Efficiency

The active solar system consists of collectors, pumps, heat exchangers, piping, storage tank, etc. Each component represents a potential for energy loss. The collectors were analyzed in the previous section. Here, the overall system performance is evaluated and compared with the estimated performance of Chapter 4.

Table 18 illustrates the average daily system performance, the actual sky clearness factor and both the actual and estimated total collected energy.

The only months during which the actual total collected energy equalled or exceeded the estimated total was during September and December.

As indicated, insolation collected averaged 23 percent for the ten month period. This long-term efficiency is lower than that estimated by currently accepted calculation procedures. It is not however, inconsistent with other installations which have to be monitored over extended periods (see references 1 and 2). Our findings closely parallel those described in reference 1 from which the following excerpt is taken.

> "The percent of sunshine tables are in themselves accurate as a statement of the mean expected percent sunshine for the specific localities shown. The application of percent of sunshine to the heat harvest table for prediction of available solar insolation may, however, lead to an overly optimistic evaluation. Reasons for this consideration follow.
>
> The percent of sunshine tables are developed by use of an instrument that detects full sunshine at any time there is no cloud interference. Thus, on a partly cloudy day, the sun may shine intermittently 25% of the time - and be recorded as such. The problem relative to solar insolation collection is that the intermittent bursts of sunshine may not be of sufficient sustained intensity as to bring collector temperatures up to operating level. Thus, absorbed solar heat may not be used - but is simply dissipated by heat transfer back to atmosphere when clouds again interfere.
>
> Another problem relative to solar collection and the percent of sunshine factor has to do with "time appearance" of the sun on a partly cloudy day. If the sun shone 50% of the time during the day and only appeared during the mid-day time range, a high percentage of the potentially available solar insolation could be collected. Conversely, if the sun again shone 50% of the time during the day, but only appeared during the early morning and late afternoon hours while cloud cover occurred during mid-day, only a small amount (if any) of the insolation would be available for collection.

TABLE 18

ACTIVE SOLAR SYSTEM EFFICIENCY SUMMARY

MONTH	AVERAGE COLLECTED ENERGY (W/m^2)	AVERAGE MEASURED ISOLATION (W/m^2)	PERCENT COLLECTED	AVERAGE * IDEAL INSOLATION W/m^2	SKY CLEARNESS FACTOR	TOTAL ACTUAL COLLECTED ENERGY (GJ) ***	TOTAL ESTIMATED COLLECTED ENERGY (GJ) **	PUMP PI (kWh)	PUMP P2 (kWh)
January	23.3	149.5	16	159.6	0.94	7.453	10.23	185.08	165.57
February	44.3	197.9	22	262.8	0.75	13.254	14.60	116.71	114.06
March	43.9	172.5	25	273.5	0.63	14.067	17.74	74.44	98.23
April	--	--	--	256.5	--	--	15.64	--	--
May	--	--	--	233.9	--	--	15.14	--	--
June	33.3	191.4	17	220.0	0.87	10.315	14.90	229.00	198.53
July	27.9	198.2	14	222.4	0.89	8.932	17.12	218.40	244.96
August	40.3	171.8	23	238.9	0.72	12.907	17.86	172.02	188.08
September	83.4	228.2	37	256.7	0.89	25.821	18.82	151.58	138.67
October	33.3	122.7	27	259.7	0.47	10.663	19.26	72.29	96.93
November	26.6	112.4	24	232.4	0.48	8.225	10.98	89.82	115.86
December	35.4	136.6	26	198.6	0.69	11.341	8.18	129.54	183.60

* From Table 5
** From Table 8
*** From Table 12

> The conventional heat harvest calculation does not take into account the highly variable nature of the percent of sun as this affects available insolation, but rather divides the month into two distinct time periods; a period of absolutely clear, sunny days and another of absolutely cloudy days. For example, if a month has 30 days and a 50% sun factor, the conventional calculation in effect states that for that month, 15 clear sunny days occurred along with 15 absolutely cloudy days. This evaluation is not realistic since it ignores the fact of intermittent cloudiness and leads to overly optimistic evaluations of available insolation."

Emergency Generator

The primary use of the emergency generator set is to provide electrical power to the facility during an electrical power outage. The generator is cooled with the building heating system water, providing heating energy to the building. When the storage tank temperature rises above 60°C, city water is used to cool the generator and the recoverable energy is lost.

The treatment plant experienced one power outage per month on the average during the monitoring period and the emergency generator was used at these times in addition to its regular exercise period each week. Due to the instability of the monitoring instrumentation during the exercise periods, the electrical energy produced by the generator is not always used in the building. Thus the electrical production meter on the monitoring system has not been active during these periods. The generator can operate on either digester-produced methane or propane. During most of the monitoring period, propane was used (see Chapter 7). Table 12 summarizes the monthly generator performance.

Gas Boiler

The methane boiler is used as a source of hot water heating when digester gas is available and more heating energy is required than that being supplied by the solar systems. For various reasons (see Chapter 7), methane was not consistently available during the monitoring period. The heating provided by the boiler was supplied by the back-up fuel, propane. Boiler usage was minimal during the monitoring period.

Table 12 summarizes the monthly boiler energy production.

Heat Pump

The water-to-water heat pump is used as a source of hot water heating when digester gas is not available and solar production is inadequate. The heat pump recovers heat from the plant effluent prior to discharge from the facility. Temperature sensors located at various points in the process lines indicated that the temperature of the wastewater as it proceeds through the plant increases. By recovering the energy from the effluent, the effluent temperature is lowered. The heat pump was the major source of heating during the winter since gas was generally unavailable and solar was inadequate.

The coefficient of performance (COP) of the heat pump varied with the temperature of the effluent, rising with a rise in effluent temperature and dropping as the effluent temperature falls (see Figure 14).

Table 19 summarizes the monthly heat pump energy production and COP performance.

TABLE 19

HEAT PUMP SUMMARY

Month	Effluent Temp (°C)	Energy Input (kWh)**		Energy Output (GJ)	COP
		Compressor	Pump		
January	7.8	6807	204	68.80	2.73
February	6.8	6717	202	64.16	2.58
March	6.1	6388	192	62.64	2.64
April*	-	(2112)	(63)	(25.3)	-
May*	-	(2327)	(70)	(28.4)	-
June	15.7	40.5	1	0.51	3.43
July	18.3	0	0	0	-
August	20.0	241.9	7	3.54	3.95
September	19.3	224.9	7	2.75	3.29
October	16.7	2327	70	28.39	3.29
November	13.7	2112	63	25.32	3.23
December	10.2	4363	131	51.08	3.16
Annual		33,660	1010	360.89	2.90

* Estimated
**1kWh = 3.6 x 10^6 J

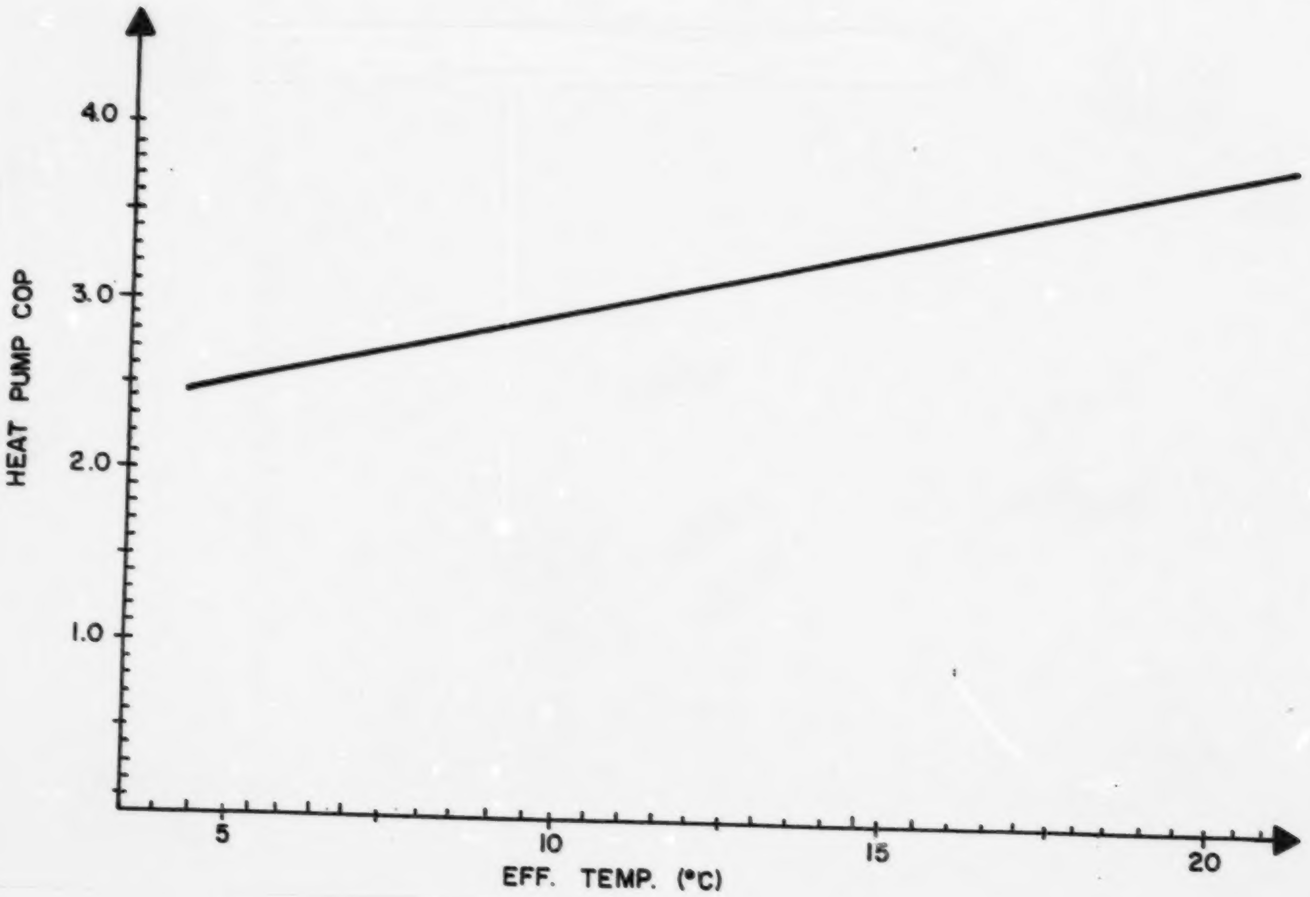

Figure 14. Heat Pump Cop vs. Effluent Temperature

Domestic Hot Water (Electric)

The Domestic Hot Water (DHW) heating is provided from either the solar storage tank when available, or the tank electric immersion heater. Table 20 below summarizes the DHW usage and electrical input required to provide supplemental heating.

TABLE 20

DOMESTIC HOT WATER HEATING SUMMARY

Month	DHW Usage (GJ)	Electrical Input kWh	Electrical Input Equiv GJ	% Supplied by Electrical
J	2.405	276.5	0.996	41
F	5.021	499.0	1.797	36
M	2.092	374.0	1.346	64
A	---	---	---	---
M	---	---	---	---
J	0.534	326.8	1.176	220
J	0.110	273.7	0.985	898
A	0.101	101.8	0.366	361
S	0.085	104.0	0.375	438
O	0.616	270.6	0.975	158
N	0.593	232.9	0.839	141
D	1.837	264.2	0.952	52

As illustrated above, during the summer and autumn, various problems were experienced with the instrumentation and controls system (See Chapter 7). This plus tank heat losses account for percentages of greater than 100% in the last column. Also, during the year the temperature was changed for various reasons. Since late summer it has been set at 43°C.

Digester Gas Generation

Wilton employs high rate, two-stage mesophilic anaerobic digestion to stabilize and reduce the quantity of sludge. Gas containing approximately 65 percent methane, 30 percent CO_2 plus trace amounts of other gases is produced as a byproduct of anaerobic digestion. This gas, being compressible, stable and combustible (22,400 kJ/m^3) represents a potentially valuable energy resource. At Wilton, the digester gas is collected and stored to be burned in the plant's boiler to supplement solar energy for space and process heating and to fuel the plant's emergency electric generator to meet some of the electric power requirements. A detailed description of the operation of Wilton's digester and digester gas systems has been excerpted from the treatment plant operation and maintenance manual and can be found in Appendix K. Basic design parameters are shown in Table 21.

TABLE 21

ANAEROBIC SLUDGE DIGESTION SYSTEM CHARACTERISTICS WILTON, MAINE

Parameter	Design (1996)	Present (March 1980)
Plant Influent Flow, m^3/d	1700	450
Sludge Production		
Quantity, m^3/d	9.6*	9.3**
Total Suspended Solids, kg/d (lb/d)	340	150
Volatile Suspended Solids, kg/d	250	125
Digester Sizing (Per Digester)		
Diameter, m	6.1	
Sidewater Depth, m	4.6	
Usable Volume, m^3	133	
Detention Time, d	13.9	15.2
Total Solids Loading, $kg/m^3/d$	2.6	1.1
Volatile Solids Loading, $kg/m^3/d$	1.9	0.95
Gas Production, m^3/kg VSS	0.63	0.50***
Gas Production, m^3/d	160	63***
Percent Methane	65	65
Gas Heat Value GJ/d****	3.55	1.39
Percent Volatile Solids Reduction***	48	57

*4% Solids (Design)
**1.6% Solids (Actual)
***Projected
****Based on 22,400 kJ/m^3

As of March 1980, approximately ninety percent of the expected initial users of the sewage collection and treatment system had been connected. Flows (and subsequent sludge quantities) were approximately 27 percent of design capacity and less than one half those projected as initial year flows. Possible reasons for lower than expected flows are:

1. Inplant programs of the major industrial users to conserve water.
2. Very little infiltration/inflow.
3. Lower per capita wastewater flows than expected from water consumption records.

As is usual in starting up a new sludge digestion facility, particularly one that is significantly underloaded, Wilton's digesters underwent an extended process of becoming acclimated and reaching steady state conditions. Consequently, very little meaningful operating data were available during the monitoring period, and the information that is available indicates that the digesters have not yet achieved optimum steady state conditions.

Low first-year flows at the treatment plant had a significant effect on the operation of the anaerobic digestion system. As can be seen from Table 21, the smaller quantity of sludge produced resulted in projected gas productions of approximately forty percent of the design quantity. Interestingly, sludge production was approximately forty-four percent of design, while plant flows were only twenty-seven percent. Volatile solids production was even closer to design rate, forty-nine percent, because Wilton's sludge was eighty-four percent volatile rather than seventy-five percent as designed. The relatively large amount of sludge being produced confirms a qualitative observation that the RBC biomass is much heavier than expected.

In March, sludge pumped to the digester averaged only 1.6 percent solids, compared to four percent design consistency. The dilution of the sludge means that the hydraulic detention time in the primary digester (15.2 days) closely approached design conditions (13.9 days).

Gas production rates for high-rate digesters should be 0.5 to 0.75 m^3/kg of volatile solids added, indicating, using the 0.5 m^3/kg figure, that 63 m^3/d should be produced. Actually, an average of 31 m^3/d were produced in March. Another "rule of thumb" for gas production is 0.75 to 1.12 m^3/kg of volatile solids destroyed. Based on volatile solids loading and detention time, one would expect volatile solids reduction to be on the order of 57 percent. Based on measurement of the secondary digester supernatant, it appears that about sixty-seven percent of the volatile solids in the raw sludge is being destroyed. At that rate, one would expect gas production to be in the range of 63 to 94 m^3/d. Actual production (31 m^3/d) fell well under this range also.

It has not been determined why gas production is not higher. Temperature, pH, volatile acids, bicarbonate alkalinity, percent methane in the gas, and volatile solids reduction, all indicators of digester performance, are within the range expected to produce good digestion. The only apparent factor which may be detrimental is solids concentration in the raw sludge (1.6 percent). Even with the diluted sludge, however, the detention time is greater than design.

Gas production, then, is approximately half that expected (31 m^3/d vs. 63 m^3/d). However, because the methane content is seventy-nine percent rather than sixty-five percent as expected, the heat value is sixty-four percent of the projected value (0.89 GJ/d vs. 1.39 GJ/d). If gas production was in the range of 63 m^3/d as the data indicate it should be, the heat value of the gas would be 1.76 GJ/d and the digesters would be energy self-sufficient (COP greater than 1.0, see Table 22).

The lower quantity of digester gas being produced changes the relative importance of the role of methane as an energy source in Wilton. At design flows it is expected that digester gas will provide thirty to thirty-five percent of Wilton's heat requirements. Initially it appears that the gas provides ten to fifteen percent. Lower gas production places more emphasis on solar and the heat pump to provide the heat energy needed.

Due to problems which arose with digester underloading and acclimation and gas handling equipment, limited digester gas production and utilization information is available for the monitoring period. Gas production stabilized and the storage, monitoring, and usage systems became fully operational during March 1980. The total heating requirement of the process was monitored and represents the heating requirement of the digester even though very little gas was produced and collected. The limited data collected on the gas production were used to arrive at a figure for gas production efficiency based on a unit of energy produced (gas) versus unit of energy used (including electrical input).

The electrical equipment associated with the methane generation equipment and daily energy usage, based on their operating schedules of Appendix D, are tabulated below. Table 22 also includes the average daily heating energy requirement and the energy production/usage ratio for the process.

From Table 22 the energy production/usage ratio indicates that we are producing slightly more than one half unit of energy for every unit used. However, if the digesters were producing as much gas as the operating data indicate they should, the ratio, even at low influent flows being experienced, would be greater than one.

Changes in operating procedures may significantly improve this ratio. Modifications to the raw sludge handling system were made in an attempt to thicken sludge before pumping it to the digesters. To date, the success of this effort has been limited, constrained by the overriding need to maintain a high quality effluent. Construction of a separate sludge thickener to be used to thicken raw sludge to at least five percent would cut the quantity of sludge being pumped to the digester by sixty to seventy percent, with corresponding decreases in heating requirements. This would increase sludge detention time in the primary digester to enable it to be operated close to standard rate, rather than high rate, while current low wastewater flows prevail. The digesters have been operated as if they were high rate (continuous mixing, heating to mid-mesophilic temperatures) and producing design gas quantities (use of high pressure storage system year round). Given the present loadings, if the sludge were thickened, significant savings in operating costs could be realized by cutting back to intermittent mixing and reducing the digester temperature to the lower mesephilic range (26 to 30°C). This would result in slower digestion and gas production, but the trade-off in lower operating costs would be cost-effective. It may also be advantageous to eliminate high pressure methane storage in the summer when active solar, with occasional boosts from the heat pump, can provide enough energy for digester heating. These changes in operation would be phased back to normal operation as digester loadings approached design conditions.

TABLE 22

DIGESTER GAS GENERATION SUMMARY

Electrical Equipment

Name	ACTUAL kWh/d(1)	ACTUAL kJ/d(2)	DESIGN kW/hd	DESIGN kJ/d
Sludge Mixer	5.97	21,500	23.88	86,000
Sludge Recirculation Pump	11.94	43,000	31.84	114,700
Sludge Pump	5.30	19,100	15.90	57,300
Sludge Dewatering Pump	0	0	0	0
Digester-Gas Recirculation Compressor	79.57	286,500	79.57	286,500
Digester-Gas HP Compressor	14.92	53,700	75.96	273,500
Total Electrical	117.70	423,800	227.15	818,000

Heating Equipment

	ACTUAL kJ/d	DESIGN kJ/d
Sludge Heat Exchanger(3)	1,084,700	3,084,100
Total Equipment Energy Input	1,508,500	3,902,100
Digester-Gas Generated Energy(4)	882,100	2,611,400

Digester-Gas Generation Efficiency

$$\frac{\text{Generated Energy}}{\text{Equipment Energy Input}} = \quad = \frac{882,100}{1,508,500} = 0.58 \qquad \frac{2,611,400}{3,902,100} = 0.67$$

NOTES:

1. See Appendix D for nameplate and operating data. Based on 20 percent motor oversizing and PF = 0.90
2. A conversion of 3,600 kJ = 1 kWh is used.
3. Average daily digester heating for March at 1.08×10^{-4} m^3/s.
4. A value of $3.6 \times 10^{-4} m^{3}/s$ at 28,300 kJ/m^3 was used as an estimate of production for March, based on meter readings from April 14 to April 24, and gas analyses indicating 79% methane content.
5. Projected to design conditions.

Electrical Usage

The total outside electrical consumption for the building was monitored and is presented in Table 23. The actual electrical power used during the 10 month monitoring period was 12.5% less than the projections of Chapter 4.

TABLE 23

TOTAL ELECTRICAL USAGE (kWh)

Month	Projected Table 3	Actual Measured
January	34,940	29,600
February	33,230	29,920
March	30,840	30,200
April	28,720	--
May	26,940	--
June	26,930	22,680
July	26,920	22,120
August	26,920	26,200
September	26,920	21,000
October	26,930	25,840
November	29,750	23,000
December	32,090	27,880

SECTION 6

ENERGY AND COST EFFECTIVENESS

The primary purpose of the alternative energy measures included in the design of the Wilton Treatment Plant was to reduce the dependence on external energy sources; to become as self-sufficient as possible. The impact of any of the energy saving measures should be a reduction in the electricity and/or fuel requirement for the plant. These measures should save money, and should do so within a specified period of time (payback period).

Each measure was evaluated for its energy and cost effectiveness and for its individual payback period. The energy produced by each measure is a known quantity and the energy required to produce the energy is either known or can be easily determined through the monitoring system data.

The cost-effectiveness analyses presented in this report follow EPA's Cost-Effectiveness Guidelines as published in the Federal Register, Vol. 45, No. 214, pp. 72983-72989 (See Appendix N). These guidelines permit differential cost escalation of energy by fuel type in accordance with tables developed by EPA. The current EPA discount rate (7-5/8%) was used. The effective life of the energy component was taken as 30 years.

The energy dollar value for the energy produced and used are based on the following rates as of spring of 1979 when the project was started.

Propane	$\$121.53/\mathrm{m}^3$	@	25.4 $\mathrm{GJ/m}^3$
	\$ 5.98/GJ	@	80% efficiency
Electricity	\$0.045/kWh	@	3,600 KJ/kWh

The fuel oil price used in this analysis is $\$330.25/\mathrm{m}^3$ @ $39.0\mathrm{GJ/m}^3$, or \$8.47/GJ, which is a 1980 price. This was used because the inflation rate on fuel oil since 1979 has been much greater than that provided for in the EPA tables and because 1980 is the effective start date for the use of those tables.

All data for this evaluation were taken from the appropriate sections of Chapter 5.

TABLE 24

CONSTRUCTION COST ESTIMATE SUMMARY

		WILTON	WILTON W/ CONVENTIONAL ENERGY	EST. COST DIFFERENCE	SERVICE LIFE (YR)
1.	SITE PREP AND LANDSCAPING	$ 102,500	$102,500	$ 0	
2.	SITE PIPING	45,000	45,000	0	
3.	BUILDING AND CONCRETE	626,800	580,200	46,600	50
4.	PROCESS	624,100	624,100	0	
5.	ELECTRICAL	110,500	100,400	10,000	20
6.	INSTRUMENTATION CONTROL	148,400	81,000	67,400	20
7.	PLUMBING	41,900	41,900	0	
8.	HEATING AND VENTILATING	96,400	96,400	0	
9.	HEAT PUMP	11,400	0	11,400	20
10.	METHANE RECIRCULATING SYSTEM (DIGESTER MIXING)	34,700	34,700	0	
11.	GENERATOR HEAT RECOVERY	2,900	0	2,900	20
12.	HP METHANE STORAGE	16,100	0	16,100	30
13.	PROPANE STORAGE	6,000	2,500	3,500	30
14.	LP METHANE STORAGE	6,100	6,100	0	
15.	SOLAR	51,000	10,000	41,000	30
16.	SPRAY IRRIGATION	15,300	15,300	0	
17.	CONTRACTOR OH AND P	224,900	224,900	0	
	TOTAL	$2,164,000	$1,965,000	$ 199,000	

PASSIVE SOLAR

Table 12 and Figures 1 and 2 illustrate the net passive solar contribution to the heating system. Tables 13 and 14 and Figure 11 summarize the monitoring data collected during the year and the actual performance of the passive array. The economic analysis is based on the difference between the total Clarifier Room heating required without the passive array and the additional heating required with the passive array.

	Energy*	Value
Output:	34.26 GJ	$290
Input:	0	0
Net Gain:	34.26 GJ	$290
Initial Investment:**		$7,016

Energy Output/Input Ratio: = N/A

Cost Effectiveness =

Simple Payback = $\frac{\$7,016}{\$\ 290} = 24$ Years

Discounted Payback:***

PW Equiv. Oil = $4,313
Initial Investment = $7,016

Therefore, Passive Solar is not cost-effective.

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* Neglecting decrease in lighting required.

** Passive panel cost of $\$158.77/m^2 \times 83.24\ m^2$, less regular insulated brick-block wall at $\$86.11/m^2 \times 72\ m^2$ equals $7,016 difference.

***Detailed Present Worth calculations can be found in Appendix N.

ACTIVE SOLAR

The active solar system provided 23% of the total heating requirement from June to March. The energy produced and pump power required are presented in Table 18. The energy and cost effectiveness and the simple payback period are based on an annual heating contribution using the monitored data plus the estimated data for the months of April and May. The pump power required for April and May are taken as the average per unit of energy delivered from the monitored period. Additional O&M costs for maintenance and replacement of coolant are estimated to be $200/yr.

	Energy	Value
Output:	153.7 GJ	$1,302
Input:	13.4 GJ (3,730 kWh)	168 (electricity) 200 (maintenance)
Net Gain	140.3 GJ	$ 934

Energy Output/Input Ratio = $\frac{153.7}{13.4}$ = 11.5

Value Output/Input Ratio = $\frac{\$1,302}{\$\ 368}$ = 3.5

Simple Payback = $\frac{\$41,000}{\$\ 934}$ = 44 Years

Discounted Payback:

PW equiv oil ouput = $ 19,300
PW electrical input = -2,200
PW net energy savings $ 17,100
Initial Investment = $ 41,000

$PW_{O\&M}$ = $ 2,200 (elec.) + $2,300 (maint.) = $4,500
Net PW = $ 41,000 + $ 4,500 - $19,300
= $ 26,200

Therefore active solar is not cost-effective. The cost of thermal energy from active solar is greater than $20/GJ, while the cost of fuel oil is $8.47/GJ, indicating the need for significant decreases in the unit cost of solar energy and/or significant increases in the cost of oil and other fuels before active solar becomes cost-effective.

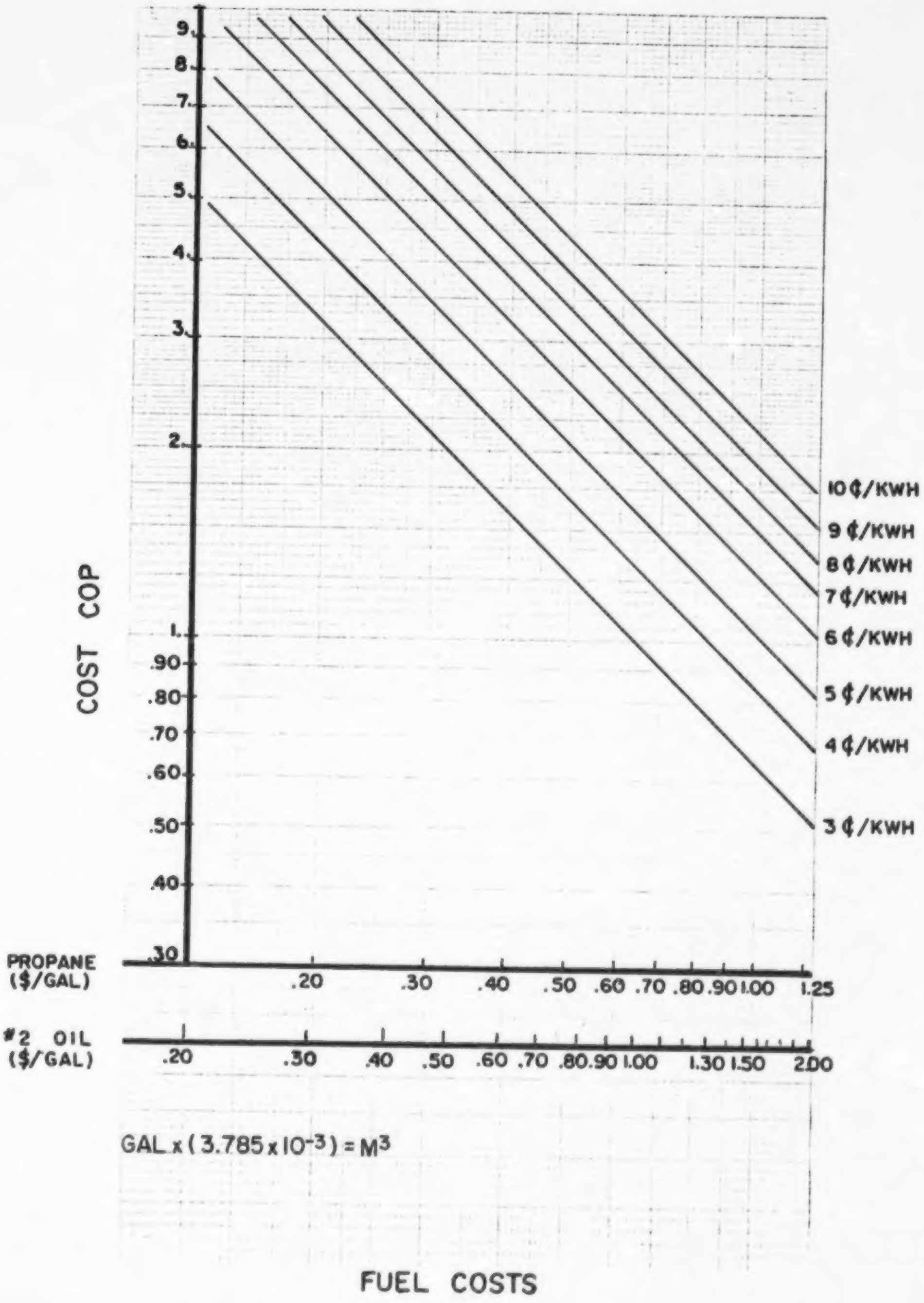
Heat Pump

The effluent-to-water heat pump provided 60% of the total heating requirement from June to March. The energy produced, power required, and other operating conditions are presented below.

To determine whether or not the heat pump system is economically feasible Figures 15 and 14 can be used as follows.

FIGURE 15

HEAT PUMP COST COP PARAMETER



Locate the alternate fuel cost on the abscissa of Figure 15 and move up to the line which represents the electrical rates (demand and fuel adjustment charges included). Read over to the ordinate to find the minimum cost COP required by the heat pump. The cost COP represents the minimum COP required such that the electrical cost of the heat pump to deliver a unit of energy equals the value of an equal unit at energy delivered by the alternate fuel.

Locate the annual average effluent temperature and read off the average heat pump COP from Figure 14. This heat pump COP represents the units of energy produced by the heat pump for each unit of electrical energy input to it.

If the cost COP is less than the heat pump COP then the heat pump is economically feasible. Otherwise, the heat pump would be producing energy but at a cost higher than using the alternate fuel directly. Once the initial economic feasibility is determined as practical, then further analysis must be done to determine the cost effectiveness of that option.

Using the monitoring data, the Wilton heat pump can be used as an example.

Alternate Fuel -

Oil at \$8.47/GJ (\$330.25/m^3; 39.0 GJ/m^3, 75% comb. eff.)

Electricity - 4.5¢/KWH

Cost COP = 2.08
Heat Pump COP = 2.90 (10°C avg.)

Therefore, economically feasible.

From Table 5.10, the cost-effectiveness can be determined.

	Energy	Value
Output:	360.89 GJ	\$3,057
Input:	124.85 GJ (34,670 kWh)	1,560 electricity 500 other O&M
Net Gain	237.32 GJ	\$ 997

$$\text{Energy Output/Input Ratio} = \frac{360.89}{124.85} = 2.9$$

$$\text{Value Output/Input Ratio} = \frac{\$3,057}{\$2,060} = 1.5$$

Cost-Effectiveness:

$$\text{Simple Payback} = \frac{\$11,400}{\$\ \ 997} = 11.4 \text{ years}$$

Discounted Payback:

PW equiv oil output = $ 45,464
PW electrical input = -20,426
PW other O&M = $ 5,834
PW net energy savings = $ 19,204
Initial investment = $ 11,400
Therefore, heat pump is cost-effective.

Emergency Generator Heat Recovery

The average generator heat recovered was 844,000 kJ/month. The generator operated on the average of one-half hour per week. During the summer it is anticipated that excess digester gas will be used in the generator thus increasing the recovered energy and decreasing the simple payback period accordingly. From Table 12 and Appendix D, the cost effectiveness can be determined.

	Energy	Value
Output:	10.13 GJ	$ 86
Input	0.09 GJ	1
Net Gain	10.04 GJ	$ 85

$$\text{Energy Output/Input Ratio} = \frac{10.13}{0.09} = 113$$

$$\text{Value Output/Input Ratio} = \frac{\$\ 86}{\$\ 1} = 86$$

Cost-Effectiveness:

$$\text{Simple Payback} = \frac{\$2{,}900}{\$\ 85} = 34 \text{ years}$$

Discounted Payback:

PW equivalent oil ouput = $ 1,279
PW electrical input = - 13
PW net energy = $ 1,266
Initial Investment = $ 2,900

Therefore, based on assumptions used, emergency generator heat recovery is not cost effective.

Air-to-Air Heat Exchanger

The air-to-air heat exchanger is incorporated on the entering air side of Unit HV-2 and the discharge of EF-4 thus heating the incoming air with the warmer exhaust air. From the testing of the heat exchanger, the thermal efficiency of this unit is 67%. The annual energy and cost effectiveness of this unit were determined utilizing the data of Table 1.

	Energy	Value
Output: (HV-2 air heating)	58.11 GJ	$492
Input: HV-2	2.88 GJ (800 kWh)	36
EF-4	3.58 GJ (994 kWh)	45
Net Gain	51.65 GJ	$411

$$\text{Energy Output/Input Ratio} = \frac{58.11}{6.46} = 9.0$$

$$\text{Value Output/Input Ratio} = \frac{\$492}{\$\ 81} = 6.1$$

Cost-Effectiveness:

$$\text{Simple Payback} = \frac{\$3,300}{\$411} = 8.0 \text{ years}$$

Discounted Payback:

PW equivalent oil output = $ 7,317

PW electrical input = -1,061

PW net energy savings = $ 6,256

Initial Investment = $ 3,250

Therefore, ventilation heat recovery is cost-effective.

Digester Gas Generation

From the limited data available on methane production and actual digester operation parameters, the energy and cost effectiveness determinations were done for the month of March only. During that month the monitoring data appear to be valid. More data are needed to further ascertain actual conditions and the effects of weather, temperature, pH levels, etc. on digester performance.

	Energy	Value
Output: (Digester Gas Production)	325 GJ*	$2,750
Input:		
Heating	398 GJ	$1,904
Electrical	153 GJ (42,700) kWh	$1,933
Net Loss =	226 GJ/Day =	$1,087

$$\text{Energy Output/Input Ratio} = \frac{325}{551} = 0.59$$

$$\text{Value Output/Input Ratio} = \frac{\$2,750}{\$3,837} = 0.72$$

Cost-Effectiveness:

Simple Payback = N/A

Discounted Payback:

PW equivalent oil output = $ 40,899
PW heat input = $ 27,214
PW electrical input = $ 25,310
PW net energy savings = $11,625

The Wilton digesters did not produce a net surplus of energy.

Table 25 summarizes the energy and cost effectiveness of all system components.

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*Based on 79 percent methane content of gas, as measured.
*No additional losses are taken here for utilization of the digester gas (combustion losses, etc.)

TABLE 25

ENERGY AND COST EFFECTIVENESS SUMMARY

Component	Output GJ	Output ($)	Input GJ	Input ($)	Initial Investment ($)	Energy Output/Input Ratio	Value Output/Input Ratio	Cost Effective
Active Solar	153.7	1,302	13.4	368	41,000	11.5	3.5	No
Passive Solar	34.26	290	0	0	7,000	32% (1)	N/A	No
Heat Pump	360.89	3,057	124.85	2,060	11,400	2.9	1.5	Yes
Generator Heat Recovery	10.13	86	0.09	1	2,900	113	86	No
Air-to-Air Heat Recovery	58.13	492	6.46	81	3,300	9.0	6.1	Yes
Digester Gas Production	325	2,750	551	3,837	N/A	0.59	0.72	No

(1) Actual average monthly solar radiation transmitted through panels from June 1, 1979 to April 1, 1980 (See Chapter 5)

(2) Neglecting Maintenance Costs

SECTION 7

OPERATIONAL PROBLEMS

During the months which the plant has operated several operational problems have been encountered. Corrective actions have been taken where practicable.

Collector Temperature Stratification

The solar collectors were put into operation in the fall of 1978 with ambient temperatures ranging between 7° and 18°C During this period, there was no problem in starting the glycol/water circulation pump P-1, which is started in response to the collector plate temperature.

In mid-winter, however, with ambient temperatures between -18° and 0°C, P-1 was not starting even though fluid temperatures at the top of the collector were dangerously high. (The locations for the collector plate thermocouples are shown in Appendix H.)

The thermocouple originally selected to control P-1 was located at the bottom of the collector array. It was discovered, at these colder outside air temperatures, that there was a temperature gradient between the lowest and highest points on the collector array of as much as 55°C. The array is 18 panels wide and 3 panels high.

The control was switched to the uppermost thermocouple which starts P-1 at the desired set point and protects the system from possible overheating leading to decomposition of the glycol solution.

Instrumentation Problems

1. A problem was encountered with solar pump P-2 which circulates water through the water side of the glycol-water/water heat exchanger. In brief, the start circuit for the pump was dependent on the glycol temperature leaving the solar collectors. This transmitter sensed an erroneously high temperature whenever the solar storage tank temperature was also high, causing both pump cycling and loss of energy back to the collectors. The problem was corrected by a change of the controlling variable.

2. The pneumatic temperature controllers, which provide input to the control logic circuits, have been found to have their set-

points drifting considerably. In one case the drift was in excess of 16°C. A contact cement is currently being used to help keep the setpoints from drifting.

3. Due to manufacturing difficulties and delivery schedules encountered, the original flow turbines were replaced by different units. This necessitated some transmitter recalibrations, etc. One of the installed turbine meters is now found to not be producing linear outputs in the range in which it is operating (HV-2). With the best delivery schedule, there was not time enough to receive and install the new unit and generate data for the monitored heating season.

4. The weather station developed a leak in the weatherproofed sensing elements which then gave incorrect readings for wind speed and wind direction. This has been repaired and the weather station has been operating satisfactorily since mid-January.

5. The sludge pump timing mechanism required revisions such that the proper sequence would be followed. The most recent revision was made in mid April which significantly reduced the amount of sludge pumped into the digester. These rates will continue to be adjusted to optimize digester performance. Once the operation has been optimized, an accurate evaluation of the digester gas system can be made.

Digester Problems

1. The underground digester gas lines to and from the high pressure storage tanks developed leaks and were repaired. As gas began being provided and these lines used, moisture got into the lines and froze, rendering the high pressure storage tanks inoperable. Since the gas lines to the equipment using gas were these same lines, the gas which was generated was lost out the vents. The lines were reopened in mid-March and have been operational since. It was believed that during the summer, due to the usage and temperatures the tanks will be experiencing, the moisture will be cleared out. However, the problem recurred during the winter of 1980-1981.

2. Due to sludge production being much less than anticipated and a lack of effective sludge thickening, digester performance and production of digester gas were significantly impaired. Minimal data were collected on digester performance, and the data that were obtained are suspect due to insufficient gas production to give the digester gas utilization system a significant trial.

SECTION 8

ENGINEERING EVALUATION

Several areas have been recognized where design modifications might significantly improve the performance of the energy systems.

Hydronic Solar System

The solar heating system should be designed to supply thermal energy to heat the digester only, not be part of an integrated space/process heating system. While theoretically more efficient, the operating difficulties associated with a highly integrated system result in significant system losses. The following guidelines apply:

a. The solar system should be designed to service the digester directly with a glycol loop through the sludge heat exchanger.

b. The solar system should be designed to "dump" excess heat into the secondary digester and/or a storage tank. A heat exchanger should be provided to recover heat from sludge transferred from the primary digester to the secondary digester and/or from sludge wasted from the secondary digester.

c. The solar/sludge heat exchange system should be designed to operate with service fluid temperature of 43° to 46°C. The effectiveness of solar thermal energy collection improves significantly with lower operating temperatures.

d. The ratio of solar collector surface area in m^2 to sludge flow in m^3/d should be approximately 25:1 (i.e., 10 m^3/d of sludge requires 250 m^2 of solar collector surface), assuming climatic conditions similar to Wilton and digester insulation of R-20.

e. A conservative evaluation of expected sludge flow should be used in sizing the solar collector array. Generally, sizing should be based on average flow over the design life, or less.

f. Solar heating system design details:

    1. The collector should be a flat plate design.

2. The collector tilt angle should be optimized for maximum yield approximately 45 days prior to and following winter solstice.

3. Systems capable of digester heating with fluid temperature of 43° to 46°C should use single glazing.

4. Systems requiring digester heating fluid temperatures greater than 48°C should use double glazed collectors.

5. The solar collector must be a low mass, quick response collector with a selective surface with an absorptivity to emissivity ratio (a/e) of 0.95/0.10.

6. The associated hydronic system instrumentation and controls must be designed to respond more quickly to the availability of useable solar energy. Generally this requires a simpler system design.

7. The solar collector array should be designed for thirty year operation without significant maintenance and no replacement.

g. The solar collector may form a roof under the following guidelines:

1. The collector absorber plate must be thoroughly thermally isolated from the building support structure.

2. All seals must be high temperature silicone or equivalent.

3. All metals must be compatible or dielectrically isolated.

4. The collector glazing elements must be capable of simple replacement.

5. The rear of the collector array should be within a heated space and be accessible from the interior.

6. The rear of the collector should have R-20 insulation.

7. The tilt angle should be a minimum of 45 degrees.

h. Domestic hot water required for plant personnel should be supplied through a takeoff heat exchanger on the main system.

As discussed below, it is doubtful that solar heating of anaerobic digester can be shown to be cost-effective under current accepted economic projections, or under any conceivable circumstances except for a small range of treatment plant sizes, perhaps 0.04 m^3/s to 0.10 m^3/s. However, if other factors (socio-political, regulatory, etc.) dictate, the above guidelines will assure the most cost-effective use of solar thermal energy for digester heating. It should be noted that recent advances in solar collection technology have incorporated many of the above guidelines.

Passive Solar Heating

1. Passive heating should be applied to "occupied" areas such as the office and laboratory. It is less effective in areas exposed to water surface such as Wilton's clarifier room but may be desirable for natural lighting purposes. Such areas should be heated minimally, with thermostats set at 5°C. The movement of wastewater in these areas will largely maintain temperatures greater than 5°C.

2. In areas to be heated to 20°C ±, passive solar collectors should be fitted with manually operated insulated shutters.

Heat Pump

1. Size the effluent pick up tank to minimize drawdown problems associated with plant flow variations.

2. Design the effluent side to facilitate normal maintenance of intake screens.

Instrumentation

Keep instrumentation as simple as possible. The instrumentation tends to become complicated when integrating solar and perhaps other alternative energy systems with the heating, ventilating and processes of the treatment plant.

Digester Gas System Design

The Wilton wastewater treatment plant's energy systems design has received a great deal of attention. Since the inception of the energy systems monitoring project, several reports have been written concerning the economic feasibility of solar-assisted anaerobic sludge digestion. It is the authors' opinion that some of these reports are optimistic, at best, and that the operating results at Wilton do not justify this optimism.

The basis for the Wilton design is that the use of flat plate hydronic solar collectors in concert with anaerobic sludge digestion is synergistic, that the low temperature thermal energy produced by the solar collectors can be used to heat the digesters, replacing a portion of the digester gas produced which would have to be burned to heat a similar nonsolar-assisted digester. The gas thus replaced can be stored for use as a fuel for the production of direct thermal energy (boiler), electrical energy (engine-generator), or mechanical energy (engine-drive). The cost-effectiveness of active solar energy production is strengthened when so combined with anaerobic digestion. Its payback is quicker because the thermal energy is needed year-round to heat the sludge. Storage of solar energy is much more efficient in the form of the compressible, combustible, gas produced as a byproduct of digestion than as hot water or air. This is the rationale advanced to support the Wilton design and used to substantiate claims of widescale cost-effective applicability in other reports.

The problem with the solar digester scenario is in its cost-effectiveness; Wilton successfully demonstrates its technological feasibility. The evidence from Wilton and elsewhere indicates, however, that the payback on active solar systems is longer than anticipated due to actual operating efficiencies being significantly lower than projected from instantaneous design data efficiencies.

The other major flaw in the solar digester scheme is that heat can be recovered, directly or indirectly, from the digester gas more cost-effectively than by using solar. A study done by Wright-Pierce to determine possible innovative and alternative technologies for use at a wastewater treatment plant being designed for Caribou, Maine indicates that if there is sufficient sludge to justify anaerobic digestion as a stabilization process, then it is more cost-effective to 1) burn the gas to heat the digesters; 2) use the gas to fuel an engine generator set to produce electricity and recover the heat given off by the engine to provide digester heating; or 3) fuel an engine-drive set to operate equipment (replacing electricity), with engine heat recovery. If sludge digestion is justified, then the heat recovered from any of the above systems will be much more significant than any feasible solar contribution. If there is not sufficient sludge to make anaerobic digestion cost-effective, then adding solar will not make it so (this is Wilton's situation). The following examples are presented in support of this contention.

Consider three treatment plants with average daily flows of 0.020 m^3/s (0.45 Mgd; Wilton's design flow), 0.044 m^3/s (1.0 Mgd), and 0.44 m^3/s (10.0 Mgd), each producing sludge at a rate of 0.22 kg dry solids/m^3. A preliminary design and cost-effectiveness analysis is performed on each plant to determine whether anaerobic digestion is cost-effective compared with lime stabliization, and if digestion is cost-effective, whether solar heating is. Costs are taken from EPA's Innovative and Aternative Technology Assessment Manual, updated to 1981 with the ENR Construction Cost Index.

I. A. 0.020 m^3/s Treatment Plant with Anaerobic Digestion

Assume: 0.22 Kg dry solids/m^3 at 5% solids
75% VSS
50% VSS reduction in digestion
digester loading rate = 1.91 kg VSS/m^3d
gas production rate = 0.75 m^3/kg VSS destroyed
heat content of gas = 22,400 kJ/m^3

1. Size of digester:

quantity of sludge = (0.02 m^3/s) (0.22 kg/m^3) (86,400 s/d) = 380 kg/d
VSS = (0.75) (380) = 285 kg/d
VSS destroyed = (0.5) (285) = 143 kg/d

$$\text{Volume of digester} = \frac{285 \text{ kg VSS/d}}{1.91 \text{ kg/m}^3\text{d}} = 150 \text{ m}^3$$

digester dimensions: diameter = 6.0 m
depth = 6.0 m

2. Digester heating requirements:

digester heat loss:

	$A(m^2)$	T avg	T max	heat loss (W) avg	heat loss (W) max
walls (U = 0.7 $W/m^2\cdot°C$)	113	29	48	2,300	3,800
floor (U = 0.85$W/m^2\cdot°C$)	30	31	31	800	800
roof (U = 0.9 $W/m^2\cdot°C$)	28	28	64	700	1,600
		Total (W)		3,800	6,200
		Daily (MWh)		0.091	0.148
		GJ/d		0.33	0.54

sludge heating:

$$(4200 \text{ J/kg°C}) (28°\text{C}) \left(\frac{380 \text{ kg/d}}{0.05} \right) = 0.89 \text{ GJ/d}$$

total heating requirement = 0.33 + 0.89 = 1.22 GJ/d, avg.
= 1.31 GJ/d, max.

3. Heat value of gas produced:
(143 kg VSS destroyed /d) (0.75 m^3/kg VSS destroyed) = 107 m^3/d
(22,400 kJ/d) (107 m^3/d) = 2.40 GJ/d
at 75% boiler efficiency, 1.80 GJ/d heat from digester gas
Therefore, heat produced from burning digester gas is sufficient to heat the digester, with 0.58 GJ/d excess.

4. Cost-effectiveness

a. Capital Cost = $255,000

b. O & M = labor and materials = $13,700/yr
electricity = $210/yr

$PW_{O\&M}$ = $13,700 (11.668) + $210 (13.094*) = $162,600

c. Value of replaced fuel (excess digester gas), assuming 75% utilization.

$$\frac{0.75}{0.75}\ (0.58\ \text{GJ/d})\ (\$8.47/\text{GJ}) = \$4.91/\text{d} = \$1{,}800/\text{yr}$$

$$PW_{\text{excess gas}} = \$1{,}800\ \ (14.872)^{*}\ \ = \$26{,}800$$

d. Net Present Worth of digesters = \$255,000 + \$162,600 - \$26,800
= \$390,800

e. Present Worth of sludge hauling and disposal = \$534,000

f. Total Present Worth of digester system = \$390,800 + \$534,000
= \$924,800

I. B. 0.020 m^3/s Treatment Plant with Lime Stabilization

1. Capital cost = \$89,000

2. O&M Cost = \$9,800
$PW_{O\&M}$ = \$ 9,800 (11.668) = \$114,300

3. $PW_{\text{lime stabilization}}$ = \$ 89,000 + \$114,300
= \$203,300

4. $PW_{\text{sludge hauling and disposal}}$ = \$569,000

5. Total PW for lime stabilization = \$772,300

II. A. 0.044 m^3/s Treatment Plant with Anaerobic Digestion

Assume: 0.22 kg dry solids/m^3 at 5% solids
75% VSS
50% VSS reduction in digestion
digester loading rate = 1.91 kg/m^3d
gas production rate = 0.75 m^3/kg VSS destroyed
heat content of gas = 22,400 kJ/m^3

1. Size of digester:

quantity of sludge = (0.044 m^3s) (0.22 kg/m^3) (86,400^s/d) = 840 kg/d

VSS = (0.75) (840) = 630 kg/d VSS
VSS destroyed = (0.5) (630) = 315 kg/d VSS destroyed

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*See Appendix N

Volume of digester = $\frac{630\ \text{kg/d VSS}}{191\ \text{kg/m}^3\text{d}}$ = 330 m^3

digester dimensions: diameter = 9.0 m
depth = 5.0 m

2. Digester heating requirements:

digester heat loss: 0.54 GJ/d (average)
0.89 GJ/d (maximum)

sludge heating - (4200 J/kg°C) (28°C) ($\frac{840\ \text{kg/d}}{0.05}$) = 1.98 GJ/d

total heating requirements = 0.54 + 1.98 = 2.52 GJ/d, avg.

= 2.87 GJ/d, max.

3. Heat value of gas produced:

(315 kg VSS destroyed /d) (0.75 m^3/kg VSS destroyed) = 236 m^3/d
(22,400 kJ/m^3) (236 m^3/d) = 5.29 GJ/d
at 75% boiler efficiency, 3.97 GJ/d heat from digester gas

Therefore, heat produced from burning digester gas is sufficient to heat digester, with 1.45 GJ/d excess.

4. Cost-effectiveness

a. Capital cost = $312,000

b. O&M cost: labor and materials = $14,000/yr
electricity = $270/yr
OW O&M = $166,900

c. Value of replaced fuel (excess digester gas) assuming 75% utilization

$\frac{0.75}{0.75}$ (1.45 GJ/d) ($8.47/GJ) (365) = $4,500/yr

PW excess gas = $66,900

d. PW digester = $312,000 + $166,900 - $66,900

= $412,000

e. PW sludge hauling and disposal = $599,000

f. Total PW for digestion = $1,011,000

II. B. 0.044 m^3/s Treatment Plant with Lime Stabilization

1. Capital cost = \$140,000
2. O & M Cost = \$ 15,300/yr
   $PW_{O\&M}$ = \$178,500
3. $PW_{\text{lime stabilization}}$ = \$140,000 + \$178,500 = \$318,500
4. PW sludge hauling and disposal = \$710,000
5. Total PW for lime stabilization= \$ 1,028,500

III. A. 0.44 m^3/s Treatment Plant with Anaerobic Digestion

Assume: 0.22 kg dry solids/m^3 at 7% solids
75% VSS
50% VSS reduction in digestion
digester loading rate = 1.91 kg/m^3d
gas production rate = 0.75 m^3/kg VSS destroyed
Heat content of gas = 22,400 kJ/m^3

1. Size of digester:

quantity of sludge = (0.44 m^3/s) (0.22/m^3) (86,400 s/d) = 8,360 kg/d

VSS = (.075) (8360) = 6,270 kg/d VSS
VSS destroyed = (0.5) (6270) = 3135 kg/d VSS destroyed

$$\text{Volume of digester} = \frac{6{,}270\ \text{kg/dVSS}}{1.91\ \text{kg/m}^3.\text{d}} = 3{,}280\ \text{m}^3$$

Digester dimensions: diameter = 18 m
depth = 13 m

2. Digester heating requirements:

digester heat loss: 2.47 GJ/d average
4.05 GJ/d max

$$\text{sludge heating} = (4{,}200\ \text{J/kg.°C})\ (28°\text{C})\ \left(\frac{8{,}360\ \text{kg/d}}{0.07} \right) = 14.04\ \text{GJ/d}$$

total heating requirements = 16.51 GJ/d, avg.
18.09 GJ/d, max.

3. Heat Value of gas produced:

(3,135 kg/d VSS destroyed) (0.75 m^3/kg VSS destroyed) = 2,350 m^3/d
(22,400 kJ/m^3) (2,350 m^3/d) = 52.67 GJ/d
at 75% boiler efficiency, 39.50 GJ/d heat from digester gas

Therefore, heat produced from buring digester gas is sufficient to heat digester with 22.99 GJ/d excess.

4. Cost-effectiveness

a. Capital Cost = $2,000,000*

b. O&M Cost: labor and materials = $24,800/yr
power = $1,800/yr

$PW_{O\&M}$ = $313,000

c. Value of replaced fuel (excess digester gas) assuming 75% utilization

$\frac{0.75}{0.75}$ (22.99 GJ/d) ($8.47/GJ) (365) = $71,100/yr

$PW_{excess\ gas}$ = $1,057,400

d. $PW_{digester}$ = $2,000,000 + $313,000 - $1,057,400

= $1,255,600

e. $PW_{sludge\ hauling\ and\ disposal}$ = $ 1,795,000

f. Total PW for digestion = $3,050,600

III. B. 0.44 m^3/s Treatment Plant with Lime Stabilization

1. Capital Cost = $ 700,000

2. O&M cost = $ 95,400/yr
$PW_{O\&M}$ = $1,113,000

3. $PW_{lime\ stabilization}$ = $700,000 + 1,113,000 = $1,813,000

4. $PW_{sludge\ hauling\ and\ disposal}$ = $2,831,000

5. Total $PW_{for\ lime\ stabilization}$ = $4,644,000

Example I.A., the 0.020 m^3/s (size of Wilton) treatment plant with anaerobic digestion is not cost-effective when compared with lime stabilization. Would adding solar heat make it cost-effective?

---

*This would be $900,000 from EPA's Innovative/Alternative Technology Manual, but experience shows this to be unrealistically low.

Assume the same size, and cost, solar heating system were added, and assume the efficiency of the system were as specified in Wilton, not as achieved. The solar heating system would then contribute 327.3 GJ/yr under climatic conditions experienced during the data gathering period in Wilton reported in this study. Assume all the gas produced in the digester (107 m^3/d) were used to run plant equipment, replacing electricity and heat were recovered from the engines. At a 25% efficiency of conversion to electricity and a 30% efficiency in the recovery of heat, the following cost-effectiveness analysis can be performed.

Gas production = (107 m^3/d) (365) = 39,055 m^3/yr

Value of replaced power:

at 25% conversion efficiency =(0.25)(39,055 m^3/yr)(22,400 KJ/m^3)
(2.78 x 10^{-4} kWh/kJ)

= 60,800 kWh/yr

= $2,763/yr @ 4.5¢/kWh

PW replaces power = $2,736 (13.094)

= $35,800

Value of recovered heat:

at 30% recovery efficiency = (0.30) (39,055 m^3/yr) (22,400 KJ/m^3)
= 262.4 GJ/yr

Total heat available =

Solar = 327.3 GJ/yr

Recovered from gas = 262.4 GJ/yr

589.7 GJ/yr

Digester heat requirement = 445.3 GJ/yr

Net excess heat = 144.4 GJ/yr (assume this can be used for space heating)

at $8.47/GJ = $1,223/yr

$PW_{\text{oil equivalent}}$ = $ 1,223 (14.872)

= $18,200

Present Worth:

Capital Cost = \$255,000 (digester) + 41,000 (solar)

= \$296,000

$PW_{O\&M}$ = \$163,000 (digester) + 4,500 (solar)

= \$167,500

$PW_{\text{replaced power}}$ = \$35,800

$PW_{\text{excess heat}}$ = \$18,200

$PW_{\text{sludge hauling and disposal}}$ = \$534,000

Total PW of solar digester system = \$296,000 + \$167,500 - 35,800 -18,200 + 534,000 = \$943,500

Total PW of digester system without solar = \$924,800

Total PW of lime stabilization system = \$772,300

It can thus be seen that adding solar heat, even under the most optomistic of circumstances, makes anaerobic digestion at the scale of the Wilton plant even less cost-effective.

A similar analysis can be done at the 0.044 m^3/s size plant (II.A.). It has been shown above that anaerobic digestion at this scale is marginally cost-effective compared with lime stabilization. Can adding solar make anaerobic digestion more cost-effective by allowing the gas to be used to run plant equipment rather than simply to keep the digester warm? Assume that the solar collector will be sized to provide sufficient heat to heat the digester along with that recovered for the gas fueled engines.

Digester gas produced = (263 m^3/d) (365) = 86,140 m^3/yr

Value of replaced power = (0.25) (86,140 m^3/yr) (22,400 kJ/m^3) (2.784×10^{-4} kWh/kJ)

= 134,100 kWh/yr

at 4.5¢/kWh = \$ 6,035

$PW_{\text{replace power}}$ = \$79,000

recovered heat = (0.30) (86,140 m^3/yr) (22,400 kJ/m^3)

= 578.9 GJ/yr

Digester heat requirements = 919.8 GJ/yr

Solar heat required = 919.8 - 578.9 = 340.9 GJ/yr

Solar heat provided by optimum Wilton-sized system = 327.3 GJ/yr

Assuming direct scale up, would need system $\frac{340.9}{327.3}$ = 1.04 times size of Wilton

Present Worth:

Capital cost = \$312,000(digesters) +1.04 (\$41,000)(solar)=\$ 354,600

$PW_{O\&M}$ = \$166,900 (digester) + 1.4 (\$4,500) (solar) = \$ 171,600

$PW_{\text{replaced power}}$ = \$ 79,000

$PW_{\text{hauling and disposal}}$ = \$ 599,000

Total PW of solar digester system = \$1,046,200

Total PW of digester system without solar = \$1,011,000

Total PW of lime stabilization \$1,028,500

Therefore, adding solar heat to free the digester gas for a "higher value" use such as fueling engines to drive equipment is not cost-effective, and in fact would make lime stabilization more cost-effective.

At the largest plant size considered, 0.44 m^3/s, there is no conceivable use for solar heat, as the heat recovered from the gas fueled engines (691.7 GJ/yr) is more than sufficient to heat the digesters (578.5 GJ/yr) and probably provide all space heating requirements, too.

The conclusions from this analysis of anaerobic digestion, with and without solar heating, compared with lime stabilization for sludge processing are as follows:

1. For wastewater treatment plant the size of Wilton's (0.020 m^3/s), anaerobic digestion is not cost-effective and adding solar heat makes it even less so.

2. For a 0.044 m^3/s wastewater treatment plant, anaerobic digestion is marginally cost-effective, but adding solar heat does not improve its cost-effectiveness and in fact makes lime stabilization more cost-effective.

3. For larger plants (0.44 m^3/s), anaerobic digestion is clearly cost-effective; and there is no use for solar heating, because all heating requirements can be met with the heat recovered from the use of digester gas.

It appears that there is no role for solar heating in association with anaerobic digestion. Based on work done by others[7], if solar heating is not cost-effective when applied to anaerobic digestion it is doubtful that it is cost-effective with any wastewater treatment process. It should be noted that no attempt has been made here to consider climatic conditions other than those encountered in Wilton, Maine, or other treatment processes. However, it is doubtful that solar heating of anaerobic digestion can be shown to be cost-effective in any climate, regardless of primary and secondary treatment processes used.

It is possible that active solar heating may be incorporated cost-effectively for space heating of treatment plants which do not have anaerobic digesters, but that is a space heating problem independent of process, and based on other studies is also very doubtful. Passive solar space heating and active solar domestic hot water heating probably can be shown to be cost-effective, depending on site conditions.

The analysis indicates that the price of conventional energy (oil, electricity) will have to increase substantially more than projected and the cost of solar heating substantially decrease before solar heating of anaerobic digestion can become cost-effective, and then only for a relatively insignificant number of small wastewater treatment plants; those large enough for anaerobic digestion to be cost-effective compared to other sludge stabilization methods, but too small for the gas produced to be sufficient to render the plant thermally self-sufficient.

Non-economic, (socio-political, regulatory) factors may mandate a greater use of solar thermal energy, in which case solar heating of anaerobic digesters may be justifiable for small facilities. The argument has been made that solar should be incorporated into wastewater treatment plants, because it is an environmentally compatible "soft" energy source and is independent of factors which might interrupt the supply of fossil fuels. The reasoning is that if there is a sudden curtailment of conventional energy supplies, public facilities such as wastewater treatment plants probably would be among the first to be cut off. Therefore, incorporation of solar energy and other alternative energy sources safeguards the operation of the treatment facility and the resultant environmental protection.

By far the most energy used in wastewater treatment is electrical energy to run equipment. Even if solar heating could be shown to be cost-effective, the impact on total energy use in treatment plants would be relatively insignificant.

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APPENDIX A

CONVERSION FACTORS

TO CONVERT FROM	TO	MULTIPLY BY
°C	°F	1.8 (±C) + 32
J	BTU	9.485 E-4
J/kg °K	BTU/lb °F	2.390 E-4
kg	lb	2.205
kg/m^3	lb/gal	8.345 E-3
kJ/m^3	BTU/ft^3	2.684 E-2
kW	BTU/h	3.412 E+3
m^2	ft^2	1.076 E+1
m^3	ft^3	3.532 E+1
m^3	gal	2.642 E+2
m^3/s	ft^3/min	2.119 E+3
m^3/s	gal/d	2.282 E+7
m^3/s	gal/min	1.585 E+4
$m^3/s\ m^2$	$gal/h\ ft^2$	8.834 E+4
M Pa	lb/in^2	1.450 E+2
W/°K	BTU/d °F	1.896
W/m^2	BTU/ft^2 d	7.613
W/m^2	BTU/ft^2 h	3.17 E-1
W/m^2 °K	$BTU/h\ ft^2$ °F	1.76 E-1

APPENDIX B
BUILDING "U" FACTORS

BUILDING AREA	FLOOR AREA (FT^2)	U (BTUH/FT^2-°F)	ROOF AREA (FT2)	U (BTUH/FT^2-°F)	WALL AREA (FT2)	U (BTUH/FT2-°F)	GLASS AREA (FT2)	U (BTUH/FT^2-°F)	SC	LIGHTING (KW)	MISC (KW)	INFILTRATION (CFM)
CLARIFIER AREA	2745	0.10	4278	0.051	N - 584 W - 496	0.091 0.091	S - 896 N - 36	0.29 0.60	0.66(T) 0.20			
OFFICE - TRUCK AREA	3088	0.10	1958	0.070	N - 1174 E - 737 W - 79	0.083 0.083 0.083	N - 261 E - 63 E(DOOR) - 153	0.57 0.24 0.20	0.23 0.55 —			183
DIGESTERS (EACH)	425	0.10	415 EA	0.05	OA - 305 INT - 260 GND - 447	0.083 0.083 0.083						
ACTIVE SOLAR COLLECTORS TOWER					60°∠ HORIZ 2124 N - 1829	0.039 0.091						

APPENDIX C

DESIGN AND ACTUAL TEMPERATURES (OUTSIDE AIR AND GROUND*)

Month	Design (°C)		ACTUAL (°C)	
	OA	Ground	OA	Ground
January	-7.8	6.7	-6.7	7.8
February	-6.7	5.6	-7.9	6.7
March	-1.1	7.2	-1.2	6.1
April	5.6	10.0	-	-
May	11.7	13.3	-	-
June	17.2	16.1	16.6	14.6
July	20.0	18.9	21.6	17.2
August	18.9	19.4	16.9	19.2
September	14.4	18.3	12.4	18.5
October	8.9	15.6	7.7	15.9
November	2.8	12.2	4.6	12.9
December	-1.1	8.9	-3.7	10.1

* Taken as ground water temperature or plant influent termperature.

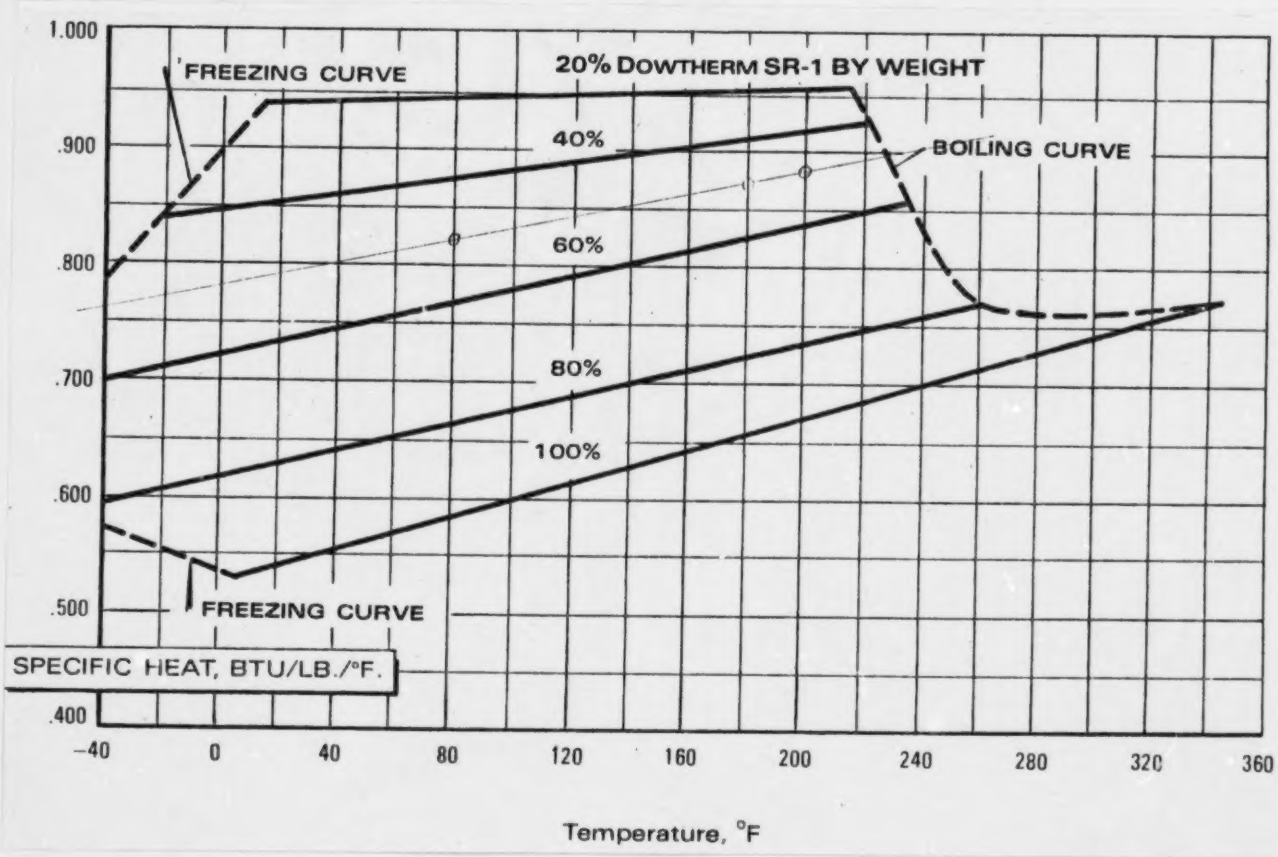
APPENDIX D

ELECTRICAL EQUIPMENT DATA AND OPERATING SCHEDULES

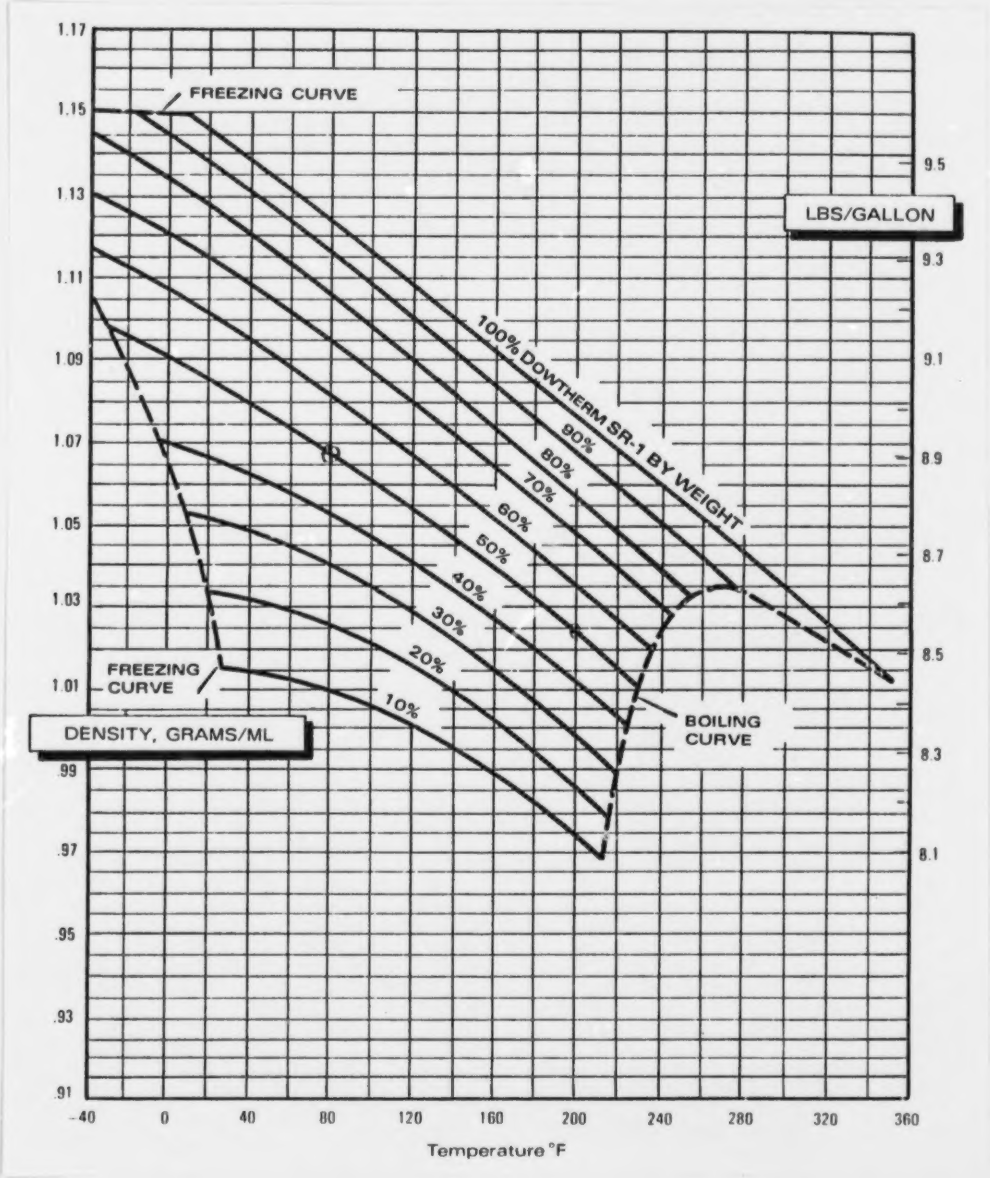
DESCRIPTION	NAMEPLATE DATA		OPERATING DATA			OPERATING SCHEDULE		MISC.
	HP	KW	V	PHASE	A	HR/DAY	DAY/WK	
HEATING & VENTILATING								
HEATING								
HV-1	1		460	3	14/16/16	8	5	2000 CFM OA
HV-2	2		460	3	32/27/28	8	5	2700 CFM OA
HV-3	1/4		120	1		1	5	900 CFM OA
UH-1	1/20							
UH-2	1/20							
UH-3	1/70							
UH-4	1/25							
UH-5	1/70							
UH-6	1/70							
UH-7	1/70							
CUH-1	1/40							
CUH-2	1/40							
CUH-3	1/40							
CUH-4	1/40		120	1		8	5	300 CFM OA
EF-1	1/40							
EF-2	1/10							
EF-3	1/40							
EF-4	2							
EF-5	1/20							
EF-6	1 1/12							
EF-7	1/16							
EF-8 DELETED	—	—	—	—	—	—	—	
EF-9	1/4							
EF-10	1/3							
EF-11	1/2							
EF-12	1/40							
EF-13	1							
EF-14	1/4							
EF-15	1/4							
EF-16	1/12							
EF-17	1/12							
EF-18	1/3							
EF-19	1/3							
P5	5		460	3	55/55/53	24	7	
P6	5		460	3	56/56/54	0		
P7	2		460	3	24/24/22	2	7	
P8	2		460	3	24/24/22	0		
REFRIGERATED AIR DRYER	1		460			15	7	
SOLAR								
P1	1		460	3	10/15/120	8	7	
P2	1		460	3	120/120/130	6	7	
HEAT PUMP								
P9	1 1/2		460	3	21/22/22	1600 HRS/YEAR		
P10	1 1/2	28.4	460	3	22/22/22	0		
HEAT PUMP-	RLA/43	LRA/205	460	3		800 FULL LOAD HRS/YR		
GENERATOR								
P3	1 1/2		460	3	21/21/22	1	1	
DOMESTIC HOT WATER								
P4	1/4		120	1				
HOT WATER HEATER		20	460	3				
TREATMENT PROCESS								
RBC MOTOR NO. 1	5		460	3	53/53/53	24	7	
RBC MOTOR NO. 2	5		460	3		0		
RBC MOTOR NO. 3	5		460	3	49/49/50	24	7	
RBC MOTOR NO. 4	5		460	3	48/49/49	24	7	
SCREW PUMP NO. 1	10		460	3	85/85/80	24	7	
SCREW PUMP NO. 2	10		460	3	75/75/75	0		
ROTOSTRAINER NO. 1	1/2					24	7	
ROTOSTRAINER NO. 2	1/2					0		
CLARIFIER NO. 1	1/2					24	7	
CLARIFIER NO. 2	1/2					0		
SLUDGE PUMP NO. 1	1					8	7	
SLUDGE PUMP NO. 2	1					0		
COMMINUTOR	1/2		460	3	10/09/10	24	7	
GRIT CHAMBER DRIVE	3/4					1	7	
GRIT BLOWER	3					1	7	
SLUDGE DEWATERING	3/4					0	0	
LUBE OIL PUMP NO. 1	1/4					24	7	
LUBE OIL PUMP NO. 2	1/4					0		
AIR COMPRESSOR NO. 1	15		460	3		4	7	
AIR COMPRESSOR NO. 2	15		460	3		0		
HOT WATER HEATER		15						
PROCESS WATER PUMP	5							
CHEMICAL FEED PUMP	1/4							
CHEMICAL TANK MIXER	1/4							
CHEMICAL TANK MIXER	1/4							
COAGULATION AGITATOR	1/4							
INTERNAL CONVEYOR	1/4							
MAIN DRIVE	1/4							
SLUDGE CONVEYOR	1/2							
HYPOMETER NO. 1	1/3					24	7	
HYPOMETER NO. 2	1/3					0		
HYPOCHLORITE GENERATOR		30				1.5	7	
SPRAY PUMP NO. 1	50							
SPRAY PUMP NO. 2	50							
DIGESTER								
SLUDGE MIXER	1 1/2					6	7	
SLUDGE RECIRCULATOR NO. 1	2					9	7	
SLUDGE RECIRCULATOR NO. 2	2							
METHANE								
METHANE RECIRCULATOR	5					24	7	
METHANE COMPRESSOR	7 1/2					3	7	
LIGHTING								
QUANITY TYPE								
7 C		84				8	5	
11 D		88				2	5	
1 E		04				2	5	
5 F		96				2	5	
20 G		1 60				2	5	
2 H		08				2	5	
8 I		1 20				2	5	
2 J		40				2	5	
3 K		24				2	5	
1 L		04				2	5	
13 M		1 3				1	7	
10 N		1 5				8	5	
9 P		1 8				2	5	
2 Q		40				2	5	
2 R		20				2	5	
8 S		56				12	7	
1 Y		08				2	5	
1 AH		20				2	5	
[illegible] BB		60				2	5	

APPENDIX E

DOWTHERM SR-I SPECIFIC HEAT AND DENSITY CURVES



APPENDIX E


FREEZING CURVE
LBS/GALLON
100% DOWTHERM SR-1 BY WEIGHT
90%
80%
70%
60%
50%
40%
30%
20%
10%
FREEZING CURVE
BOILING CURVE
DENSITY, GRAMS/ML
1.17
1.15
1.13
1.11
1.09
1.07
1.05
1.03
1.01
.99
.97
.95
.93
.91
9.5
9.3
9.1
8.9
8.7
8.5
8.3
8.1
-40
0
40
80
120
160
200
240
280
320
360
Temperature °F

APPENDIX F

ASHRAE MEAN PERCENTAGE OF POSSIBLE SUNSHINE FOR SELECTED LOCATIONS

MEAN PERCENTAGE OF POSSIBLE SUNSHINE FOR SELECTED LOCATIONS

STATE AND STATION	YEARS	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT.	NOV	DEC	ANNUAL
ALA. BIRMINGHAM	56	43	49	56	63	66	67	62	65	66	67	58	44	59
MONTGOMERY	49	51	53	61	69	73	72	66	69	69	71	64	48	64
ALASKA, ANCHORAGE	19	39	46	56	58	50	51	45	39	35	32	33	29	45
FAIRBANKS	20	34	50	61	68	55	53	45	35	31	28	38	29	44
JUNEAU	14	30	32	39	37	34	35	28	30	25	18	21	18	30
NOME	29	44	46	48	53	51	48	32	26	34	35	36	30	41
ARIZ. PHOENIX	64	76	79	83	88	93	94	84	84	89	88	84	77	85
YUMA	52	83	87	91	94	97	98	92	91	93	93	90	83	91
ARK. LITTLE ROCK	66	44	53	57	62	67	72	71	73	71	74	58	47	62
CALIF. EUREKA	49	40	44	50	53	54	56	51	46	52	48	42	39	49
FRESNO	55	46	63	72	83	89	94	97	97	93	87	73	47	78
LOS ANGELES	63	70	69	70	67	68	69	80	81	80	76	79	72	73
RED BLUFF	39	50	60	65	75	79	86	95	94	89	77	64	50	75
SACRAMENTO	48	44	57	67	76	82	90	96	95	92	82	65	44	77
SAN DIEGO	68	68	67	68	66	60	60	67	70	70	70	76	71	68
SAN FRANCISCO	64	53	57	63	69	70	75	68	63	70	70	62	54	66
COLO. DENVER	64	67	67	65	63	61	69	68	68	71	71	67	65	67
GRAND JUNCTION	57	58	62	64	67	71	79	76	72	77	74	67	58	69
CONN. HARTFORD	48	46	55	56	54	57	60	62	60	57	55	46	46	56
D. C. WASHINGTON	66	46	53	56	57	61	64	64	62	62	61	54	47	58
FLA. APALACHICOLA	26	59	62	62	71	77	70	64	63	62	74	66	53	65
JACKSONVILLE	60	58	59	66	71	71	63	62	63	58	58	61	53	62
KEY WEST	45	68	75	78	78	76	70	69	71	65	65	69	66	71
MIAMI BEACH	48	66	72	73	73	68	62	65	67	62	62	65	65	67
TAMPA	63	63	67	71	74	75	66	61	64	64	67	67	61	68
GA. ATLANTA	65	48	53	57	65	68	68	62	63	65	67	60	47	60
HAWAII, HILO	9	48	42	41	34	31	41	44	38	42	41	34	36	39
HONOLULU	53	62	64	60	62	64	66	67	70	70	68	63	60	65
LIHUE	9	48	48	48	46	51	60	58	59	67	58	51	49	54
IDAHO, BOISE	20	40	48	59	67	68	75	89	86	81	66	46	37	66
POCATELLO	21	37	47	58	64	66	72	82	81	78	66	48	36	64
ILL. C[illegible]	30	46	53	59	65	71	77	82	79	75	73	56	48	65
CHICAGO	66	44	49	53	56	63	69	73	70	65	61	47	41	59
SPRINGFIELD	59	47	51	54	58	64	69	76	72	73	64	53	45	60
IND. EVANSVILLE	48	42	49	55	61	67	73	78	76	73	67	52	42	64
FT. WAYNE	48	38	44	51	55	62	69	74	69	64	58	41	38	57
INDIANAPOLIS	63	41	47	49	55	62	68	74	70	68	64	48	39	59
IOWA. DES MOINES	66	56	56	56	59	62	66	75	70	64	64	53	48	62
DUBUQUE	54	48	52	52	58	60	63	73	67	61	55	44	40	57
SIOUX CITY	52	55	58	58	59	63	67	75	72	67	65	53	50	63
KANS. CONCORDIA	52	60	60	62	63	65	73	79	76	72	70	64	58	67
DODGE CITY	70	67	66	68	68	68	74	78	78	76	75	70	67	71
WICHITA	46	61	63	64	64	66	73	80	77	73	69	67	59	69
KY. LOUISVILLE	59	41	47	52	57	64	68	72	69	68	64	51	39	59
LA. NEW ORLEANS	69	49	50	57	63	66	64	58	60	64	70	60	46	59
SHREVEPORT	18	48	54	58	60	69	78	79	80	79	77	65	60	69
MAINE, EASTPORT	58	45	51	52	52	51	53	55	57	54	50	37	40	50
MASS. BOSTON	67	47	56	57	56	59	62	64	63	61	58	48	48	57
MICH. ALPENA	45	29	43	52	56	59	64	70	64	52	44	24	22	51
DETROIT	69	34	42	48	52	58	65	69	66	61	54	35	29	53
GRAND RAPIDS	56	26	37	48	54	60	66	72	67	58	50	31	22	49
MARQUETTE	55	31	40	47	52	53	56	63	57	47	38	24	24	47
S. STE. MARIE	60	28	44	50	54	54	59	63	58	45	36	21	22	47
MINN. DULUTH	49	47	55	60	58	58	60	68	63	53	47	36	40	55
MINNEAPOLIS	45	49	54	55	57	60	64	72	69	60	54	40	40	56
MISS. VICKSBURG	66	46	50	57	64	69	73	69	72	74	71	60	45	64
MO. KANSAS CITY	69	55	57	59	60	64	70	76	73	70	67	59	52	65
ST. LOUIS	68	48	49	56	59	64	68	72	68	67	65	54	44	61
SPRINGFIELD	45	48	54	57	60	63	69	77	72	71	65	58	48	63
MONT. HAVRE	55	49	58	61	63	63	65	78	75	64	57	48	46	62
HELENA	65	46	55	58	60	59	63	77	74	63	57	48	43	60
KALISPELL	50	28	40	49	57	58	60	77	73	61	50	28	20	53
NEBR. LINCOLN	55	57	59	60	60	63	69	76	71	67	66	59	55	64
NORTH PLATTE	53	63	63	64	62	64	72	78	74	72	70	62	58	68
NEV. ELY	21	61	64	68	65	67	79	79	81	81	73	67	62	72
LAS VEGAS	19	74	77	78	81	85	91	84	86	92	84	83	75	82
RENO	51	59	64	69	75	77	82	90	89	86	76	68	56	76
WINNEMUCCA	53	52	60	64	70	76	83	90	90	86	75	62	53	74
N. H. CONCORD	44	48	53	55	53	51	56	57	58	55	50	43	43	52
N. J. ATLANTIC CITY	62	51	57	58	59	62	65	67	66	65	54	58	52	60

MEAN PERCENTAGE OF POSSIBLE SUNSHINE FOR SELECTED LOCATIONS

STATE AND STATION	YEARS	JAN	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG	SEPT.	OCT	NOV	DEC.	ANNUAL
N. MEX. ALBUQUERQUE	28	70	72	72	76	79	84	76	75	81	80	79	70	76
ROSWELL	47	69	72	75	77	76	80	76	75	74	74	74	69	74
N. Y. ALBANY	63	43	51	53	53	57	62	63	61	58	54	39	38	53
BINGHAMTON	63	31	39	41	44	50	56	54	51	47	43	29	26	44
BUFFALO	49	32	41	49	51	59	67	70	67	60	51	31	28	53
CANTON	43	37	47	50	48	54	61	63	61	54	45	30	31	49
NEW YORK	83	49	56	57	59	62	65	66	64	64	61	53	50	59
SYRACUSE	49	31	38	45	50	58	64	67	63	56	47	29	26	50
N. C. ASHEVILLE	57	48	53	56	61	64	63	59	59	62	64	59	48	58
RALEIGH	61	50	56	59	64	67	65	62	62	63	64	62	52	61
N. DAK. BISMARCK	65	52	58	56	57	58	61	73	69	62	59	49	48	59
DEVILS LAKE	55	53	60	59	60	59	62	71	67	59	56	44	45	58
FARGO	39	47	55	56	58	62	63	73	69	60	57	39	46	59
WILLISTON	43	51	59	60	63	66	66	78	75	65	60	48	48	63
OHIO, CINCINNATI	44	41	46	52	56	62	69	72	68	68	60	46	39	57
CLEVELAND	65	29	36	45	52	61	67	71	68	62	54	32	25	50
COLUMBUS	65	36	44	49	54	63	68	71	68	66	60	44	35	55
OKLA. OKLAHOMA CITY	62	57	60	63	64	65	74	78	78	74	68	64	57	68
OREG. BAKER	46	41	49	56	61	63	67	83	81	74	62	46	37	60
PORTLAND	69	27	34	41	49	52	55	70	65	55	42	28	23	48
ROSEBURG	29	24	32	40	51	57	59	79	77	68	42	28	18	51
PA. HARRISBURG	60	43	52	55	57	61	65	68	63	62	58	47	43	57
PHILADELPHIA	66	45	56	57	58	61	62	64	61	62	61	53	49	57
PITTSBURGH	63	32	39	45	50	57	62	64	61	62	54	39	30	51
R. I. BLOCK ISLAND	48	45	54	47	56	58	60	62	62	60	59	50	44	56
S. C. CHARLESTON	61	58	60	65	72	73	70	66	66	67	68	68	57	66
COLUMBIA	55	53	57	62	68	69	68	63	65	64	68	64	51	63
S. DAK. HURON	62	55	62	60	62	65	68	76	72	66	61	52	49	63
RAPID CITY	53	58	62	63	62	61	66	73	73	69	66	58	54	64
TENN. KNOXVILLE	62	42	49	53	59	64	66	64	59	64	64	53	41	57
MEMPHIS	55	44	51	57	64	68	74	73	74	70	69	58	45	64
NASHVILLEE	63	42	47	54	60	65	69	69	68	69	65	55	42	59
TEX. ABILENE	14	64	68	73	66	73	86	83	85	73	71	72	66	73
AMARILLO	54	71	71	75	75	75	82	81	81	79	76	76	70	76
AUSTIN	33	46	50	57	60	62	72	76	79	70	70	57	49	63
BROWNSVILLE	37	44	49	51	57	65	73	78	78	67	70	54	44	61
DEL RIO	36	53	55	61	63	60	66	75	80	69	66	58	52	63
EL PASO	53	74	77	81	85	87	87	78	78	80	82	80	73	80
FT. WORTH	33	56	57	65	66	67	75	78	78	74	70	63	58	68
GALVESTON	66	50	50	55	61	69	76	72	71	70	74	62	49	63
SAN ANTONIO	57	48	51	56	58	60	69	74	75	69	67	55	49	62
UTAH, SALT LAKE CITY	22	48	53	61	68	73	78	82	82	84	73	56	49	69
VT. BURLINGTON	54	34	43	48	47	53	59	62	59	51	43	25	24	46
VA. NORFOLK	60	50	57	60	63	67	66	66	66	63	64	60	51	62
RICHMOND	56	49	55	59	63	67	66	65	62	63	64	58	50	61
WASH. NORTH HEAD	44	28	37	42	48	48	48	50	46	48	41	31	27	41
SEATTLE	26	27	34	42	48	53	48	62	56	53	36	28	24	45
SPOKANE	62	26	41	53	63	64	68	82	79	68	53	28	22	58
TATOOSH ISLAND	49	26	36	39	45	47	46	48	44	47	38	26	23	40
WALLA WALLA	44	24	35	51	63	67	72	86	84	72	59	33	20	60
YAKIMA	18	34	49	62	70	72	74	86	86	74	61	38	29	65
W. VA. ELKINS	55	33	37	42	47	55	55	56	53	55	51	41	33	48
PARKERSBURG	62	30	36	42	49	56	60	63	60	60	53	37	29	48
WIS. GREEN BAY	57	44	51	55	56	58	64	70	65	58	52	40	40	55
MADISON	59	44	49	52	53	58	64	70	66	60	56	41	38	56
MILWAUKEE	59	44	48	53	56	60	65	73	67	62	56	44	39	57
WYO. CHEYENNE	63	65	66	64	61	59	68	70	68	69	69	65	63	66
LANDER	57	66	70	71	66	65	74	76	75	72	67	61	62	69
SHERIDAN	52	56	61	62	61	61	67	76	74	67	60	53	52	64
YELLOWSTONE PARK	35	39	51	55	57	56	63	73	71	65	57	45	38	56
P. R. SAN JUAN	57	64	69	71	66	59	62	65	67	61	63	63	65	65

Based on period of record through December 1959, except in a few instances.

These charts and tabulation derived from "Normals, Means, and Extremes" table in U.S. Weather Bureau publication *Local Climatological Data*

APPENDIX G

ENERGY USAGE RECORDS

CONSTRUCTION PHASE

1978	KWH	KW	F.A.	$
8-19/ 9-19		52	.0089	412.67
9-19/10-18	11760	42	.0130	485.22
10-18/11-1	7120	42		284.05

OPERATIONAL PHASE

1978				
11-1/11-16	9560	60	0.0146	384.95
11-16/12-18	22720	64	0.0130	838.27
1979				
12-18/1-17	20360	60	0.0112	768.90
1-17/2-15	19280	64	0.0118	771.90
2-15/3-19	22120	64	0.0141	889.75
3-19/4-18	21880	60	0.0157	898.36
4-18/5-17	20400	60	0.0172	883.96

PROPANE USAGE

1979	Gallons	$
1-12	651	302.15
1-25	535	248.15
2-8	501	232.23
2-21	100	53.40
2-26	886	410.88
3-8	381	169.12
3-8	57	25.18
12-15	1710.3	793.58
12-30	828	384.19

APPENDIX H

THERMOCOUPLE LOCATIONS (ACTIVE COLLECTORS)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
					A	X														
	1				B	X				X	X									
					C	X														
					A	X														
W	2	X			B	X				X	X				X				X	E
					C	X														
					A	X														
	3	X			B	X					X									
					C	X														

APPENDIX I

HEAT PUMP SPECIFICATION DATA

A. Manufacturer: Carrier

B. Total heat output: 320,000 BTUH 26.66 tons

C. Condenser side:
   1. 40 GPM heating system water.
   2. Leaving water temperature: 130°F.
   3. Entering water temperature: 114°F.
   4. Water pressure drop: 13.5 ft.
   5. Refrigerant saturated discharge temperature: 140°F.
   6. Electric input at full load: 28.4 KW.
   7. $\text{COP} = \frac{\text{Heat Output}}{\text{Electrical Input}} = 3.3$

D. Evaporator Side:
   1. Fluid: Sewage effluent with 10 ppm chlorine residual and minimal suspended solids.
   2. Fluid Flow: 60 gpm.
   3. Entering Water Temperature: 50°F.
   4. Leaving water temperature: As required.
   5. Maximum water pressure drop: 5 PSI.

E. Refrigerant: R-22.

F. Saturated suction temperature: 36°F.

G. Acceptable variation in performance from specified conditions:
   1. Total heat output: 320,000 BTUH minimum.
   2. Condenser water flow: None.
   3. Leaving condenser water temperature: None.
   4. COP: 3.1 minimum.
   5. Evaporater water flow: 80 GPM maximum.
   6. Leaving evaporater water temperature: 42°minimum.
   7. Refrigerant: Others will be acceptable providing they meet performance requirements.

BOILER SPECIFICATION DATA

Manufacturer: Raypack (Raytherm Model WTTB516)

BTU input: 516,000

BTU output: 412,800

Controls: Modulating gas valve

Fuel: Digester Gas (Methane); 600BTU/ft^3

AIR-TO-AIR HEAT EXCHANGER SPECIFICATION DATA

Manufacturer: Des Champs Laboratories Inc.
Z-Duct Energy Recovery UnitMode/1000B-68-A-6

Dimensions: 39" H x 17" W x 22" L

Pressure Drop @ 1000 CFM: 0.79" w.c.%

Efficiency @ 1000 CFM: 68%

Max. Operating Temperature: 350°F

ELECTRICAL GENERATOR SPECIFICATION DATA

Manufacturer: Onan Corp.
Model No. 115WA15R

Rating: 277/480v, 3 phase, 4 wire, 60 Hz
115 kw, 144 kva (Proprane)
70 kw, 87.5 kva (Digester Gas)

Engine: Four cycle, water cooled, gas vaporfired. Dual fuel gas vapor carburation system with automatic changeover from Digester Gas (500 BTU/ft^3) to Propane (2,500 BTU/ft^3)

APPENDIX J

DATA VERIFICATION

INTRODUCTION

The information contained herein is the procedures, data, and calculations used to verify the energy monitoring system meter calibration factors for the Wilton Wastewater Treatment Plant. These calibration factors are then use in the analysis of the data to determine the energy usage of the facility and the contribution made by each energy subsystem.

Each monitoring system will be addressed individually with design parameters and verification calculations included with each section.

All equipment operating data is either from actual measured conditions or from design conditions. Temperature readings were taken where possible with in-the-line installed thermometers. All such measured and/or design conditions appear in the respective monitoring system.

Summary

The verified calibration factors for all monitoring equipment is summarized below.

Designation	Description	Calibration Factor
Btu Meters		
A	Generator to Storage	1500 Btu/count
B	Storage to Heating	1200 Btu/count
C	Solar Production	2000 Btu/count
D	Solar to Heating	2000 Btu/count
E	Domestic Hot Water	1000 Btu/count
F	Methane Boiler	2200 Btu/count
G	Heat Pump	2200 Btu/count
H	Digester Heating	660 Btu/count
I	Building Heating	2200 Btu/count
J	HV-1 Heating	2000 Btu/count
K	HV-2 Heating	1000 Btu/count
Pyranometers:		
B/A	Total Active	206.98 Btu/count
B/P	Total Passive	205.37 Btu/count
B2	Non-Reflected Active	227.67 Btu/count
B3	Indoor Passive	312.51 Btu/coun
Wattmeters:		
Pump P-1		0.01 kwH/count
Pump P-2		0.01 kwH/count
Heat Pump		0.10 kwH/count
Domestic Hot Water		0.10 kwH/count
Generator		0.10 kwH/count
Miscellaneous:		
Master Electric Meter		40 kwH/count
City Water Meter		

Bristol Meter Calibration Factors - Unverified

B1 A	2750 cts/hr	4/20/79	AJL
B2	2500 cts/hr	4/20/79	AJL
B1 P	1750 cts/hr	4/20/79	AJL
B3	1150 cts/hr	4/20/79	AJL

BTU "A"	1500 Btu/ct	4/20	AJL
"B"	1200 Btu/ct	4/20 & 5/04	AJL & PLT
"C"	2000 Btu/ct	5/4	PLT
"D"	2000 Btu/ct	4/20	AJL
"E"	1000 Btu/ct	4/20	AJL
"F"	2200 Btu/ct	4/20	AJL
"G"	2200 Btu/ct	5/04	PLT
"H"	660 Btu/ct	7/27	PLT
"I"	2200 Btu/ct		
"J"	2000 Btu/ct	5/04	PLT
"K"	1000 Btu/ct	2/28/80	PLT

kwH	Generator	0.10	kwH/ct	5/24	BHM
kwH	Heat Pump	0.10	kwH/ct	5/24	BHM
kwH	DHW	0.10	kwH/ct	5/24	BHM
kwH	P1	0.10	kwH/ct	5/24	BHM
kwH	P2	0.01	kwH/ct	5/24	BHM
kwH	Master	Multiplier = kwH/ct		6/01	PLT

B1	Pyranometer Eppley PSP S/N 17274F3	7.54mv/cal/min-cm
B2	Pyranometer Eppley PSP S/N 17273F3	7.26mv/cal/min-cm
B3	Pyranometer Eppley PSP S/N 17317	6.67 mv/cal/min-cm

Moore Transmitter Calibrations

Btu Loop	S/N	Frequency Full Scale (Hz) _____	GMP	Range
A	58379	175.5	75	B
B	58380	147.8	64.8	B
C	58380	136.4	60.0	B
D	58384	139.5	60.0	B
E	58389	1334	5	E
F	58385	202	88	C
G	58388	200	88	C
H	58387	206	88	C
I	58386	207	88	C
J	58381	92.3	40.0	A
K	58382	190	20	B

Building Orientation

To properly evaluate the solar collector performance the actual building siting must be accurately known.

To do this, local solar noon (LS Noon) was determined and measurements were taken at that time. The calculations and results of this evaluation as that the solar collector away is facing west of South (Time South) by 2.3°. All calculations for the determination will now be based upon either due south or the 2.3° W of South.

Wilton, Maine, Latitude and Longitude:

Latitude = 44° north

Longitude = 69° west

Wilton Solar Time Calculations

July 6, 1979

LST = LCT + Eq. of Time

LCT = LST - Eq. of Time

LCT = 12:00 H - -:05 = 12:05 PM

LCT = EST + 20 min.

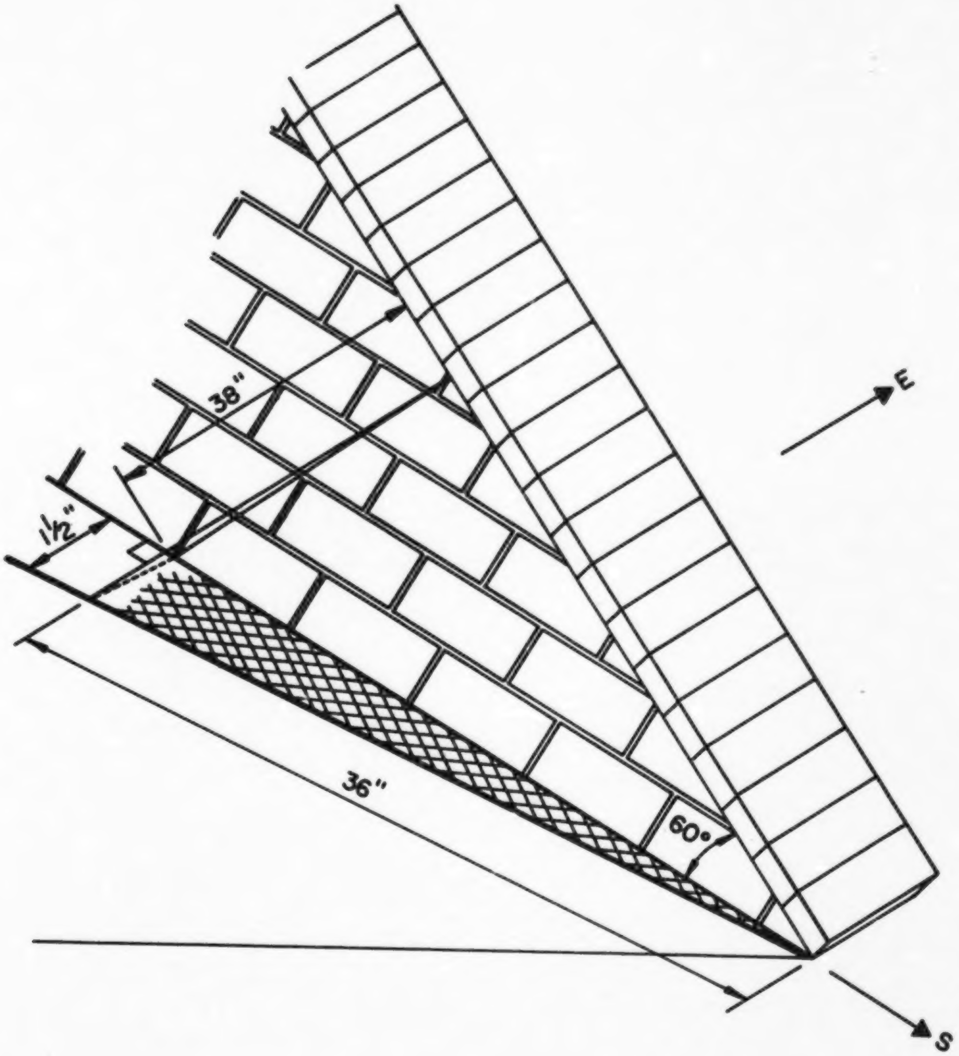
EST = LCT - 20 = 12:05 - 20 = 11:45 AM

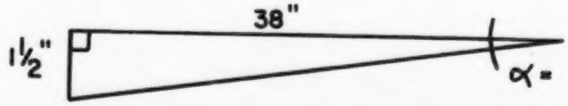
EDST = EST + 1 hr.

EDST = 11:45 + 1 hr. = 12:45 PM

= Local Solar Noon

JULY 6, 1979 12:45 PM EDST


38"
1½"
36"
60°
E
S



$$\alpha = \tan^{-1} \frac{1.5}{38} = 2.3^\circ \text{ W of South}$$

Pyranometer Verification

Pyranometer B1

Eppley Model PSP S/N 17274P3

Calibration Data: 10.81 x 10^{-6}V/Wm^{-2}

(7.54 m v/cal/cm^{2}- min)

Pyranometer B2

Eppley Model PSP S/N 17273F3

Calibration Data: 10.41 x 10^{-6} V/Wm^{-2}

(7.26 mv/cal/cm^{2-}min)

Pyranometer B3

Eppley Model PSP S/N 17317F3

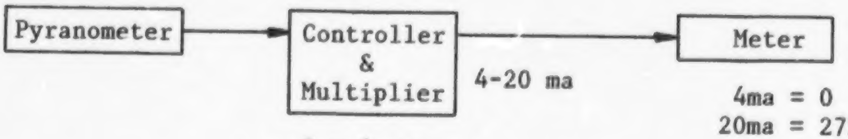
Calibration Data: 9.56 x 10^{-6} V/Wm^{-2})

(6.67 mv/cal/cm^{2}-min)

B1 Active Meter Calibration	2750 cts/hr	Full Scale
B1 Passive Meter Calibration	1750 cts/hr	Full Scale
B2 (Shielded) Meter Calibration	2500 cts/hr	Full Scale
B3 (Interior) Meter Calibration	1150 cts/hr	Full Scale

Effective Active Solar Area = 1286 ft^2

Effective Passive Solar Area = 812 ft^2



4ma = 0 counts/hr
20ma = 2750 counts/hr

0 = 4 ma
2 x calib. factor = 20 ma(Full Scale)

To calibrate the metering system take two times the pyranometer calibration as the full scale reading level.

2 cal/min-cm^2 = 442.6 Btuh/ft^2

= 442.6 x 1286 = 569,184 btuh

$$\frac{\text{569,184 Btuh}}{\text{2750 counts/hr}} = \text{206.98 Btu/clunt}$$

B-1 Passive

1750 counts/hr = 2 cal/cm^2- mm = 442.6 Btuh/ft^2

= 442.6 x 812 = 359,391 Btuh

$$\frac{\text{359,391 Btuh}}{\text{1750 counts/hr}} = \text{205.37 Btu/count}$$

B-2 Shielded

2500 counts/hr = 2 cal/cm^2 min = 442.6 Btuh/ft^2

= 442.6 x 1286 = 569,184 Btuh

$$\frac{\text{569,184 Btuh}}{\text{2500 counts/hr}} = \text{227.67 Btu/count}$$

B-3 Indoor

1150 counts/hr = 2 cal/cm^2 - min = 442,6 Bthu/ft^2

= 442.6 x 812 = 359,391 Btuh

$$\frac{\text{359,391 Btuh}}{\text{1150 counts/hr}} = 312.51$$

For this day solar noon corresponds to 12:41 PM EDST. The solar insolation data, as tabulated in Appendix F, is listed as the insolation intercepted from 30 min. before to 30 min. after the listed hour where hour 12 corresponds to the insolation received from 11:30 AM to 12:30 PM LST.

The following table gives the total insolation anticipated and measured for the various hours.

B1 Active

Hour(LST)	Insolation from Tables (Btuh/ft^2)	Insolation from Pyranometer (Btuh/ft^2)
10	207.0	204.4
11	234.5	217.6
12	244.0	210.2
1	234.5	222.1
2	207.0	196.4
5 Hr Avg.	225.4	210.1

$$\% \text{ Difference} = \frac{(225.4 - 210.1)}{225.4} \times 100 = 6.8\%$$

The tabulated data is for a clear sky. As can be seen from the Pyranometer strip chart, there were occasional clouds. Also, there was a bit of haze in the air. Therefore, this pyranometer appears to be operating properly.

B1 Passive

B1 Active and B1 Passive should be identical on a Btuh/ft^2 basis since they are the same pryanometer.

Hour	B1 Active (Btuh/ft^2)	B1 Passive (Btuh/ft^2)
10	204.4	207.4
11	217.6	221.1
12	210.2	213.0
1	222.1	225.6
2	196.4	199.3
5 Hr Avg.	210.1	213.3

$$\% \text{ Difference} = \frac{(210.1 - 213.3)}{210.1} \times 100 = 1.5\%$$

This difference is obviously due to the equipment accuracy since we are using the same pyranometer. This error is not bad though. We could correct for this if later data makes it appear that this is a constant difference. But for now, the B1 Passive Meter appears to be operating properly.

B 2 Active (Shielded)

B1 Active and B2 with the shield removed should be equal.

Hour	B1 Active (Btuh/ft^2)	B2 Active (Btuh/ft^2)
11	217.6	210.9
12	210.2	202.7
1	222.1	215.6
3 Hr. Avg.	216.6	209.7

$$\%\ \text{Difference} = \left(\frac{216.6 - 209.7}{216.6} \right) \times 100 = 3.1\%$$

This difference is due to the equipment accuracy and possibly a bit due to additional refleciton on the bottom pyranometer, B1.

B2 with the shield in place should be lower than B1 active by the amount of reflection.

	B1A (Btu/ft^2 - day)	B2 (Btu/ft^2 -day)
June 14 Data	1947	1724
June 15 Data	1941	1744
Average	1944	1734

$$\%\ \text{Difference} = \left(\frac{1944-1734}{1944} \right) \times 100 = 10.8\%$$

10.8% - 3.2% = 7.6% due to reflection. This seems reasonable, therefore B2 appears to be operating properly.

B3 (Indoor)

B1 Passive and B3 should be equal were the passive panels removed and the sky diffuse of B1 Passive eliminated. To estimate the B1 Passive value we used the shield on B2 raised to the overhead position. The use the B2 data with the appropriate scale factors, to simulate the B1 Passive.

B2 (Upper Shielded) at 2 pm, 6-15-79 Data, is 182.9 Btuh/ft^2.

B3 (Indoor) at 2 pm, 6-15-79 Data, is 176.3 Btuh/ft^2.

$$\% \text{ Difference} = \frac{(182.9 - 176.3)}{182.9} \times 100 = 3.6\%$$

Taking the % differences into account the % difference between B2 (unshielded) and B3 (Indoor) is 3.6 - 3.2 - 1.5 = 1.1%.

Thus it would appear that B3 is operating properly and that the errors are equipment accuracy errors and especially in this case because the shielding was not perfect and the reflections of the two are not identical.

APPENDIX K

DESCRIPTION OF ANAEROBIC SLUDGE DIGESTION SYSTEM
DIGESTER GAS SYSTEM*

ANAEROBIC SLUDGE DIGESTION*

Description of Process

Processing the sludges that are produced and removed in a wastewater treatment plant is one of the most costly and complex tasks that the operator faces. After processing, these sludges must be disposed of in an environmentally acceptable fashion. One of the methods that has been used widely for processing organic sludges is the anaerobic digestion process. The specific objectives of anaerobic digestion include the following:

1. Decompose sludge organics to a stabilized humus.
2. Reduce the mass and volume of sludges.
3. Obtain useful by-products.
4. Destroy or control agents of disease and infection.

Nature of Sludges

Sludges processed by anaerobic digestion are derived from the primary rotostrainers and final clarifiers. Sludge solids collected on the primary rotostrainers consist mostly of larger organic and inorganic solids present in the raw wastewater. Sludge from the final clarifiers consists primarily of the organic biomass developed in the rotating biological contractor system.

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* From: Operation Manual, Wastewater Treatement Plant
Wilton, Maine (Volume I)

Prepared by WRIGHT-PIERCE, January 1979

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The quantity of sludge solids reaching the digester depends on the removal efficiency of the sludge producing processes within the treatment plant. The removal efficiencies of processes within the plant usually are determined on a routine basis. After several months of operating experience, an operator should be able to forecast the quantities of sludge produced within the plant. Even though data on sludge quantities and characteristics are not essential for day-to-day operation, the operator should have some of this quantitative information for planning estimates and plant troubleshooting. Further discussion of sludge origin and quantities may be found elsewhere.

Digester feed sludge composition may be characterized broadly according to VS content and TS concentration. Primary screenings and RBC sludge characteristically have different TS and VS compositions. The TS concentration of the primary rotostrainers is a function of the screen opening size and operating conditions such as grease blinding. The TES concentration of the settled secondary sludge is dependent on both surface settling rate and solids detention time in secondary settling tanks. On the other hand the volatile content of both primary and secondary sludges depends on both sludge origin and its in-plant history.

Biological solubilization and decomposition causes the volatile content the volatile content to decrease as sludge processing time increases. The age of a sludge is usually quantifed by a process parameter referred to as SRT. For a given process, it is defined as the time that a typical sludge particle resides or is retained within the process such as the RBC, final settling, or sludge holding processes.

The primary screenings have short SRT's limited to the time they spend in the raw sludge holding tank. The VS range of the screenings will vary considerably, depending on the nature of the raw wastewater. The probable range is 60 to 75 percent.

No definitive date is available on SRT for RBC sludge, but it may generally be assumed to be short (2 to 5 days). The VS of fresh RBC sludge is 72 to 84 percent. SRT in the raw sludge holding tank is a matter of hours, depending on the sludge transfer pump control timer and plant loading, so little breakdown, or solubilization, of VS will take place in the holding tank. Also, due to short residence times in all processes, temperature will remain relatively low even in summer, preventing VS solubilization. Thus, the sludge pumped to the digesters should have a high VS contract, on the order of 70 - 75 percent.

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* Note: Much of this section was edited from WPCF MOP 11.

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Biochemistry

Successful, complete anaerobic digestion of municipal sludge is a three-stage series reaction (Figure 5-4). In the first step, the complex organic compounds in the solid portion of feed sludge are solubilized or dissolved by enzymes that are secreted by anaerobic bacteria. These enzymes liquify a portion of the organic solids into complex soluble organic compounds. Not all of the organic solids are solubilized, however. First, some complex organic solids that can be solubilized only by a specific class of enzymes. These specific enzymes may not be present in sufficient concentrations. These are two reasons why "well digester" municipal sludges always contain residual organic matter.

Following solubilization, the complex organic molecules are converted (Figure 5-4) into simpler components by a general class of microorganisms known as the volatile acid formers. The products of the acid-forming reaction are short-chain fatty acids, primarily acetic, propionic, and butyric acid (volatile acids). Other products of the acid-forming steps (Figure 5-4) can proceed over a broader range of environmental conditions than the other steps.

The third and final step in the series anaerobic digestion reaction for municipal sludges i the formation of methane. Tracer studies indicate that a large fraction of this end product is formed primarily from acetic acid (Figure 5-4) The other fraction of methane produced is by decomposition of propionic and other volatile acids. It is essential that the volatile acids, which are formed in the second step of the digestion process, are converted to methane. If the volatile acids are not converted to methane, they will accumulate and ultimately lower the digester pH. This accumulation cold lead to the inhibition of methane bacteria and result in process failure. Temperature, pH, ionic concentration,s and oxidation-reduction potential must be maintained within certain ranges to sustain the population of methane formers. These bacteria are more sensitive and fragile than the acid forming bacteria. Furthermore, the growth rate of methanogenic bacteria is lower than the acid forming bacteria. Therefore, it takes a longer time for the methane bacteria to recover the inhibition or shock conditions.

Combining of Stages

In the operation of Wilton's digester facilities, all three steps or stages in the series reaction, that is solubilization, acid formation, and methane information, occur simultaneously in a given digester. If the operator would withdraw a sample of digesting sludge for chemical analysis, the result would show compounds representative of each step in the series reaction. Some confusion exists over the meaning of the term "stage" in reference to anaerobic digesterion. The Wilton wastewater treatment plant has been described as having "two stage Digestion". What is really meant is that a quantity of feed sludge is routed through two digesters connected in series. The sludge is initially fed to a heated digester in which it undergoes solubilization, acid formation, and methane

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EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN EPA FORM 237)
PAGE NUMBER
TYPING GUIDE SHEET

formation. The nominal residence time in the first digester is 14 days at design flow. Digested sludge is then transferred to a second digester that has the same configuration as the first tank. In the second tank, approximately 2 to 10 percent of the original biodegradable organics may still be solubilized and converted into volatile acids and finally methane. The principal function of the second digester, however, is to provide quiescent conditions for separation of solids and supernatant removal. Instead of "two stage digestion", the operator should use the terms "primary-secondary digestion".

Completely Mixed Digestion

In conjunction with primary-secondary digestion, Wilton utilizes complete mixing in the primary tank. In a completely mixed tank or reactor, the materials flowing into the tank are instantaneously mixed or diluted throughout the entire tank. An any instant of time, the composition of a sample taken from the tank effluent would be identical to that of a sample taken anywhere in the tank.

A completely mixed digester operating mode offers several significant advantages over an unmixed system. These include:

1. Very quick dilution and dispersion of incoming raw sludge is achieved, thereby decreasing the likelihood of toxicity, inhibition, or thermal shock problems. Inhibitory by-products of the digestion process are likewise dispersed.

2. Buffering alkalinity is distributed throughout the tank, thus aiding pH control.
3. Intimate food (sludge) to mass (anaerobic microorganisms) contact is attained.
4. Smaller safety factors in reaction design (due to non-uniform flow, solids concentration, and chemical composition of raw sludge) are required.
5. Grit and other nondegradable particles are kept in suspension, significantly decreasing deposition and accumulation of debris.
6. Scum is kept in suspension, preventing the buildup of a thick scum blanket which may significantly decrease useable digester volume.
7. Uniform temperatures are maintained throughout the reactor.

Reduction of Volatile Matter

One of the main objectives of anaerobic digestion is the decomposition or reduction of the organic fraction of digester feed sludge. In sludge analysis, the organic fraction is estimated by determining the volatile content of the sludge. The operator must bear in mind, however, that a standard VS analysis measures both biodegradable organics and the organic materials that will not decompose during anaerobic digestion.

Unlike aerobic processes, such as the activiated sludge process in which 80 to 98 percent of the dissolved volatile material is removed, VS reduction in an anaerobic digester is substantially lower. Even in the case of a well-operated digester, a VS reduction in excess of 60 to 79 percent is unlikely.

The reduction of VS by anaerobic digestion may vary considerably from digester to digester. Moreover, the amount of VS reduction obtained within a given digester is dependent on a number of variables. One of the most important variables is the raw sludge composition. Some sludges contain materials such as cellulose that are solubilized at a very slow rate. Once solubilized, however, the complex orglanics generally will decompose. As a result, the rate of solubilization may limit the degree of VS reduction.

Another characteristic of the VS reduction calculation is that its value fluctuates from day to day. Fluctuations are caused by changes in volatile content of the feed sludge, by sharp changes in sludge loading rate, and by changes in reactor conditions such as mixing or temperature. If VS reduction is calculated, it should be based on a monthly average and not on daily values. The VS reduction in a digester is highly dependent on the initial VS composition of the raw sludge. All other things being equal, a raw sludge with a volatile content of 75 percent will have a significantly larger VS reduction than a raw sludge having a 65 percent VS concentration.

Care must be taken in the use of VS reductin data. It may be useful for assessing the relative performance of a given digester facility. It is unrealistic to expect digesters from several different municipalities to achieve the same percentage reduction of volatile content, however. Each facility will vary. If it is desired to establish whether a sludge is adequately digested, a more rational criterion based on the degree of gasifiction achieved is preferred. Digestion may be considered complete if 90 to 95 percent of total gasification has been achieved.

Organic Loading

One of the fundamental design and operational parameters of biological treatment processes is the rate of substrate or food addition per unit mass of microorganixms. This is called the organic loading rate, OLR. In activated sludge processes, the organic loading rate is expressed as the F:M ratio or process loading intensity in units of pounds or organic material (expressed as BOD, COD or TOC) per pound of MLVSS per day.

MLVSS is a convenient approximation of the relative concentration of micro-organisms in the activated sludge process. Unfortunately, there is no equivalent analysis for estimating the microbial population in an anaerobic digester. Anaerobic bacterial solids cannot be separated from the digesting organic sludge solids. Nevertheless, an organic loading rate approximation may be made because the actual concentration of

EPA Form 2350-6 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

methanogenic organisms in a digester changes quite slowly. Therefore, if the weight of organisms in a volume of digester is relatively constant, the organic loading rate for the digester may be expressed as the weight of organic or volatile feed sludge solids added per volume of digester per day, for example, lb VS/day/cu. ft.

The organic loading rate is significant because it influences the rate of gas production and the stability of the anaerobic digestion process. The volume of gas produced from each pound of VS destroyed will range from 10 to 18 cu. ft. Furthermore, the rate of gas production is nearly proportional to the rate of organic loading. This is true for both the average 24-h loading rate and the instataneous loading rate. Problems may arise when digesters are loaded with quantities of organic solids on an infrequent basis, for example, only once a day. In this situation, gas production rate may be so vigorous that severe foaming may result.

Digester operating temperature is the criterion used to classify a digester as being mesophilic or thermophilic. Mesophilic indicates that the digester's nominal operating temperature falls in the range of 80° to 100° F. The thermophilic range is 110° to 140°F. Wilton's digesters are designed to operate in the mesophilic range, at 95°F. The operator should experiment with various temperatures in the mesophilic range to determine the temperature that is best for Wilton's digesters. Once the optimum temperature is found the primary digester should be maintained as closely as possible to that temperature.

Sludge withdrawn after 90 percent of the available gas has been produced will not create a nuisance. Most of the VS that will decompose readily are solubilized within a matter of hours or a few days. The remainder of the volatile material is solubilized and converted at a much slower rate. Therefore, the organic solids remaining in the sludge after withdrawal will continue to break down at a rate similar to the slow rate at which organic decay occurs in forests. Solubilized, complex organics in the sludge withdrawn from a digester still may be converted to methane if anaerobic conditions prevail. On the other hand, they may be oxidized to CO_2 and water in an air or oxygen environment. In either case, the nuisance intermediates, that is, volatile acids, H_2S, mercaptans, amines, will not be present in sufficient concentrations to create a major problem.

Gas Production

Gas production is one of the most important measurable digestion parameters. The total volume, rate, and composition of gas produced are indicative of a digester's performance. The total volume of gas produced, assuming that the feed sludge composition remains constant, is a measure of the degree of reaction in the digester. The number of cubic feet of gas produced per pound of VS entering the tank should be calculated by the operator. The results should be charted for a number of months to characterize digester performance. Once characterized according to gas production per pound of solids destroyed daily, determinations may be made and compared with the long-term value previously calculated. Deviation from the norm may be indicative of a change in the extent of digestion or a change inthe character of the VS being fed.

Gas production rate and gas composition also provide information about digester performance. The rate of gas production should be measured on the digester gas line from each digester. Composition is determined by an Orsat analyzer.

Several months of oeprating experience should indicate the rate of gas production to be expected from the addition of a know quantity of volatile sludge solids. If the rate of gas production begins to fall below the expected level, then careful surveillance of the process should be initiated to assess the cause and protect against ultimate digester failure. Gas composition, like gas production rate, is also a useful gauge for determining the state of a digester.

Digester stability may be affected by excessive organic loading rates. This is true for both the average 24-h loading rate and the instantaneous loading rate. Excessive organic loading rates may yield a rapid build-up of short-chain fatty acids, also referred to as total volatile acids, that may inhibit the methane-forming organisms.

Organic loading rate is a key parameter used to characterize the two different modes of municipal digester design and operation. These two modes are referred to as standard rate digestion and high rate digestion.

Standard Rate and High Rate Digesters

As digester design evolved to include heated, closed tanks with gas collectioncapabilities, operating experience indicated that the organic loading rate should be maintained between 0.03 and 0.01 lb Vs/day/cu ft. The section of a standard rate digester in which active digestion occurs is only a portion of the total digester volume. Because standard rate digestion does not incorporate sludge mixing, the digester is stratified into zones, thus severly reducing the effective volume of the tank.

Wilton's digesters are designed for high-rate digestion. High-rate digestion evolved from design and operating improvements made to the original standard rate digester. Mixing capability was added to digester designs, thus providing homogeneity throughout the tank. Sludge feeding and withdrawal were provided on a continuous or nearly continuous basis. Furthermore, improvements in heating equipment yield a more uniform distribution of temperature throughout the reactor. As a result of these improvements, plant operating experience has indicated that an organic loading rate of 0.1 to 0.4 lb VS/day/cu ft may be used for high-rate digestion.

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 237)
TYPING GUIDE SHEET

The high-rate and standard rate terminology, which has been used for years, is somewhat deceptive. The terms do no mean that the rate at which solid organic materials are converted to methane is faster in a high-rate digester than in a standard rate digester. Actually, the chemical reaction rate constant is the same in both digesters, provided the temperature is identical. The high-rate design provides conditions that are more favorable to anaerobic digestion, however.

Mixing, improved heating, and the more continuous feed that characterize hihg-rate digesters provide a more complete interaction of the microorganisms and th organic sludge materials. Therefore, it should be remembered that high rate refers to the higher organic loading rate rather than the rate of conversion from solids to methane.

Time and Temperature

In general, the detention time needed to obtain complete digestion decreases with increasing temperature. In the filed, however, a temperature change of ±5.

Because the most important end product of anaerobic decomposition is methane, the methane concentration in the gas ususally indicates whether the anaerobic reactions have gone to completion. If the methane fraction of the gas begins to decrease, then the series reaction (Figure 5-4) is probably no going to completion, and the digester eventually will fail unless some corrective measures are taken.

Description of Facilities

Tank Construction

The two digesters in Wilton are identical in construction. They are cylindrical, 20 ft. in diameter by 17 ft. deep at the sides with conical floors sloping 4:1 to a center well. They are constructed of reinforced cast-in-place concrete. The walls are 1 ft. thick. fixed steel dome-shaped covers are provided for each digester.

Because the digesters must be heated, they are well insulated. The perimeter is insulated with 1 3/4 inch rigid styrofoam and is faced with brick. The tanks are mostly below grade to take advantage of the insulating value of the earth. The roofs are insulated with 2 inches of urethane and covered with 4-ply built up roofing.

The digester control room is located between and north of the digesters. Its two levels contain the appurtenant equipment.

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

Digestion and Solids Separation Tanks

Although solids destruction and stabilization are the primary functions of municipal digestion facilities, there is also a secondary function. Normally, the solids remaining in the digested sludge must be concentrated for subsequent treatment or disposal. This operation is referred to as solid-liquid phase separation.

As a result, most municipalities that use high-rate digestion require some type of solid-liquid separation unit. The separation unit is the secondary digester which is physically identical to the primary digester. Because of the vigorous gasification and supplemental mixing in a high-rate digester, the excess gas dissolved within the sludge (mostly CO_2) tends to keep the digested sludge particles suspended. Thus, gravity separation of supernatant and solids can be a slow process.

Besides solid-liquid separtion, facilities usually are provided for temporary storage of concentrated digested sludge. The digested sludge holding tank lies between the digester control room and the clarifier room. Its function is to store digested sludge which is periodically transferred to it until such time as a sufficient quantity is accumulated to dewater.

Digester Covers

Wilton's digesters are provided with fixed steel covers. They are equipped with a positive displacement feed and drawoff arrangement because it is essential that the volume of new sludge added to the digester equals the volume removed. Otherwise, a negative gas pressure may develop under the cover, thus allowing atmospheric air to enter. In certain concentrations, oxygen mixed with methane may proudce an explosive atmosphere. The low and high explosive limits of methane in air are 5.3 and 14.0 percent, respectively. This means that when the volume ratio of CH_4: air is greater than 5.3 percent and less than 14 percent an explosive situation exists. Because "pockets" or localized concentrations of CH_4 may exist, extreme care should be exercised whenever methane exists in any amounts.

Heating

Raw sludge is fed directly to the primary digester. Mixed sludge from the primary digester is recirculated through the digester heat exchanger where the digester calls for heat. The last exchange is A Don Oliver flow sludge heater, located in the eastern end of the lower level digester room.

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Mixing

Mixing is also a very important part of a high-rate digestion. A firm definition of "adequate mixing" is not known, but operating experience indicates that mixing at least equivalent to pumped recirculation of the entire contents of the tank over a period of 12 to 24 hours is recommended.

Pumps

Two centrifugal pumps located in the lower digester room are used for all internal digester sludge transfer functions.

Piping

Sludge piping is generally fiberglass reinforced plastic (FRP).

Safety Equipment

Digester gas is a potential safety hazard. The following safety equipment is provided at Wilton:

1. Pressure relief, vacuum relief, and flare traps;
2. Waste gas flare trap;
3. Flare traps on all gas-utilizing equipment lines;
4. Drip traps;
5. Outside vented lines from gas equipment;
6. Explosive gas detectors

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EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 337)
TYPING GUIDE SHEET

APPENDIX L

SHADING COEFFICIENT DUE TO OVERHANG OF PASSIVE COLLECTOR ARRAY

January	1.00
February	0.97
March	0.96
April	0.94
May	0.87
June	0.86
July	0.87
August	0.93
September	0.96
October	0.97
November	1.00
December	1.00

APPENDIX M

ACTIVE SOLAR SPECIFICATION DATA

The active solar collectors were specified as follows:

Quantity 54	
Gross Area 27.75 ft^2	1498 ft^2
Aperture 23.82 ft	1286 ft^2
Number of glazing lites	2
Glazing thickness	3/16 inch
Type Tempered	
Transmissivity	90.5%/Sheet
Insulation - Fiberglass R-22 (changed to 5" ISOSYANURATE R-40)	
Water - glycol solution 50/50	
Solution temperature 120°F - 140°F	

Efficiency determined by a straight line passing
thru 58% at T/I of .2
and 33% at T/I of .6
for a clear day

$$\text{Efficiency} = \frac{\text{Q heat removed from panel by fluid}}{\text{panel effective ft}^2 \times \text{solar Insolation}}$$

Solar insolation = I (BTU/Hr - ft^2)

Q heat removed = W x Cp x (T out - T in)

= Flow rate x specific heat x DT

Effective area = Aperature

$$\text{T fluid avg.} = \frac{\text{T out} - \text{T in}}{2} \ {}^\circ\text{F}$$

Insolation/site data includes:

45° Latitude North

60° Tilt angle

Collector facing 5° West of South

Monthly Average Ambient Temperatures

Jan.	24°F	Jul.	71°F
Feb.	25°F	Aug.	70°F
Mar.	35°F	Sept	62°F
Apr.	45°F	Oct.	54°F
May	56°F	Nov.	41°F
June	65°F	Dec.	28°F

5 MPH wind speed

APPENDIX N

EPA COST-EFFECTIVENESS ANALYSIS GUIDELINES AND PRESENT WORTH FACTORS

Procedure as outlined in proposed changes to EPA cost-effectiveness analysis, Federal Register Vol. 45, No. 214, pp. 72984-72989. Factors in EPA Cost-Effectivness Analysis.

Effective Design Life = 30 years

Discount Rate = 7 5/8%

PWF_{30} (7 5/8%, 30 yrs) = 11.668

PWF_{20} (7 5/8%, 20 yrs) = 10.098

PWF_{10} (7 5/8%, 10 yrs) = 6.825

GF_{10} (7 5/8%, 10 yrs) = 3.899

$PWFGS_{10}$ (7 5/8%, 10 yrs) = 26.11

$MPWF_{10}$ (7 5/8%, 10 yrs) = 4.843

$MPWFGS_{10}$ (7 5/8%, 10 yrs) = 12.762

$MPWF_{20}$ (7 5/8%, 20 yrs) = 2.684

$MPWFGS_{20}$ (7 5/8%,20 yrs) = 6.121

Energy Cost Escalation Factors were taken from Tables 1 and 2, Region I Column, FR Vol. 45, No. 214, pp. 72986-72987. For the ten year period 2000-2010, Cost Escalation Factors for distilled oil and electricity were assumed to be 0.28 and 0, respectively.

Generalized Present Worth Formula:

$$\begin{aligned} PW_x = R_x\ & (PWF_{30}) + 0.1\,(CEF_{10})\,(PWFGS_{10}) + (CEF_{10})\,(MPWF_{10}) \\ & + 0.1\,(CEF_{20})\,(MPWFGS_{10}) + (CEF_{10})\,(CEF_{20})\,(MPWF_{20}) \\ & + 0.1\,(CEF_{30})\,(MPWFGS_{20}) \end{aligned}$$

where PW_x = Present Worth of Item X

R_x = Annual Cost of Item X

CEF = Cost Escalation Factor for Item X

Subscript_{10} = 0-10 years (1980-1990)

$_{20}$ = 10-20 years (1990-2000)

$_{30}$ = 20-30 years (2000-2010)

for oil:

$$\begin{aligned} PW_{oil} = R_{oil} \quad & 11.668 + (0.1)\ (0.34)\ (26.611) + (0.34)\ (4.843) \\ & + (0.1)\ (0.22)\ (12.762) + (0.34)\ (0.22)\ (2.684) \\ & + (0.1)\ (0.28)\ (6.121) \\ = R_{oil}\ & (14.872) \end{aligned}$$

for electricity:

$$\begin{aligned} PW_{elec.} = R_{elec.} \quad & 11.668 + (0.1)(0.19)\ (26.611) + (0.19)\ (4.83) \\ & + (0.1)\ (0)\ (12.762) + (0.19)\ (0)\ (2.684) \\ & + (0.1)\ (0)\ (6.121) \\ = R_{elec.}\ & (12.094) \end{aligned}$$